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TRI-SERVICE PERSPECTIVES ON MICROCLIMATE COOLING OF PROTECTIVE CLOTHING IN THE HEAT

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This Tri-Service report evaluates the effectiveness of various microclimate cooling systems in alleviating the thermal burden imposed on our service members by wearing protective clothing in the heat. The report summarizes the findings from studies involving liquid-cooled, air-cooled, and ice-cooled systems conducted by the U.S. Army, U.S. Navy, and the U.S. Air Force. While both liquid- and air-cooled systems are shown to remove significant quantities of body heat, more evidence seems to favor air-cooled systems. In general, most commercially available microclimate cooling systems are shown not to be operationally suitable for the Services' needs. To date, the ideal microclimate cooling system suitable for most military situations has not been developed or identified. However, prediction modeling analyses indicate that with heat extraction rates of 300-400 watt, microclimate cooling can be a significant force multiplier for the Services in most desert and tropic climates.

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TECHNICAL REPORT

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TRI-SERVICE PERSPECTIVES ON MICROCLIMATE COOLING OF PROTECTIVE CLOTHING IN THE HEAT

Edited by: Kent B. Pandolf

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AN UPDATED REVIEW: MICROCLIMATE COOLING OF PROTECTIVE OVERGARMENTS IN THE HEAT

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A REVIEW: US NAVY (NCTRF) EVALUATIONS OF MICROCLIMATE COOLING SYSTEMS

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USAF PHYSIOLOGICAL STUDIES OF PERSONAL MICROCLIMATE COOLING: A REVIEW

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April 1995

FORWARD

This Tri-Service report evaluates the effectiveness of microclimate cooling systems in alleviating the thermal burden imposed on our service members by wearing chemical protective clothing under varying environmental conditions. The report summarizes the findings from a series of studies involving microclimate cooling conducted by the U.S. Army, U.S. Navy, and the U.S. Air Force. A similar version of this same report will be published as Volume I of a two volume series by The Technical Cooperation Program on the same topic. The second volume will include reports on microclimate cooling from the United Kingdom, Canada, and Australia.

OVERALL CONTENTS

TECHNICAL REPORT

NO. T 95-7

AN UPDATED REVIEW: MICROCLIMATE COOLING OF PROTECTIVE OVERGARMENTS IN THE HEAT

by

Kent B. Pandolf, Julio A. Gonzalez and Michael N. Sawka

March 1995

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EXECUTIVE SUMMARY

The effectiveness of microclimate cooling systems in alleviating the thermal burden imposed upon soldiers by the wearing of chemical protective clothing under varying environmental conditions has been examined in a series of studies conducted by the U.S. Army Research Institute of Environmental Medicine on the copper manikin, in the climatic chambers and in the field. Liquid-cooled undergarments (LCU) and air-cooled vests (ACV) were tested under environmental conditions from 29°C, 85% rh to 52°C, 25% rh. These parameters were chosen to simulate conditions which may be encountered in either armored vehicles, or in desert or tropic climates. We have reviewed eight studies using LCU, one study using ice-cooled vests and eight studies using ACV. LCU tests investigated the effect on cooling when the proportion of total skin surface covered by the LCU was varied. ACV tests examined the effects on cooling during different combinations of air temperature, humidity and air flow rates. Additionally, these combinations were tested at low and moderate metabolic rates. The findings from these LCU and ACV studies demonstrate that a) cooling can be increased with a greater body surface coverage by a LCU and b) evaporative cooling with an ACV is enhanced at low metabolic rates with optimal combinations of air flow rates and dry bulb/dew point temperatures, resulting in the extension of tolerance time. Modeling analyses were performed to depict the effects of microclimate cooling, over a broad range of heat extraction rates, on extending endurance time in a desert and tropic climate. These analyses indicate that with heat extraction rates of 300-400 watts, microclimate cooling is a significant force multiplier.

INTRODUCTION

High temperature and humidity in the work place have been of major concern to diverse industries ranging from gold mining to space exploration (17,22,25,35). Cognizant of the problem of heat stress on soldiers working in heat outdoors, military commanders have also become aware of the effects of heat on soldiers on maneuvers in enclosures such as tanks and airplane cockpits or encapsulated inside nuclear-biological-chemical (NBC) protective clothing (1,13,33). Characterized by low moisture permeability and high insulating properties (clo ~2.0; i_m/clo ~0.15), NBC clothing, while necessary to prevent noxious agents from reaching the skin, also prevents the normal dissipation of body heat generated metabolically or gained from the environment (18). NBC protective clothing includes a chemical protective overgarment, overboots, mask with hood and protective gloves. Each of these articles of clothing in various combinations constitutes a given MOPP (Mission Oriented Protective Posture) Level, designated as I, II, III or IV. MOPP I is characterized by the overgarment being worn while the overboots, mask/hood and gloves are carried; MOPP II is characterized by the overgarment and overboots being worn while the mask/hood and gloves are carried; MOPP III is characterized by all but the gloves being worn and; MOPP IV is characterized by all protective clothing articles being worn (also referred to as "complete NBC protective clothing"). In addition, the very bulk of the protective clothing renders the individual less efficient in movement due to the "friction-drag" between the layers, and actually increases the metabolic heat generated by the wearer on a given task, increasing the need to dissipate the heat (34). The

intent of this paper is to review the ongoing research program concerning microclimate cooling which is being conducted by the Environmental Physiology and Medicine Directorate at the U.S. Army Research Institute of Environmental Medicine (USARIEM).

Initial studies documenting the thermal burden imposed on the wearer of NBC clothing were done by Joy and Goldman in 1968 (16). They studied men in protective clothing who walked for 50 min on an outdoor course exposed to various ambient temperatures (>24°C), humidities, and solar radiative loads. The short length of time that subjects could tolerate such conditions was found to depend more upon impaired heat dissipation than upon the ambient thermal load (12). In fact, they estimated that protective clothing in environments above 24°C decrease tolerance time for continuous moderately heavy physical work to only thirty min (14).

Joy and Goldman's investigations were continued in a 1969 study of an amphibious landing of marines in protective clothing on a Caribbean shore. None of these encapsulated men were able to complete the mission; the study concluded that "it is medically unfeasible to operate in a tropical environment in any of the protective uniforms which were tested" (36). It was clear that even when rest breaks were provided, those in protective wear continued to gain heat. Similar thermal stress on men wearing protective clothing inside an XM-1 tank, parked in the desert sun, was documented by Toner in 1981 (32). Outside the tank, WBGT ranged from 25.7°C to 31°C while inside the tank, the range was 26.8°C to 35°C. When the tank was sealed under these conditions, the men could only remain inside for 80-124 min before heat strain ensued.

Two approaches have been developed to alleviate heat stress in the working individual: macroclimate and microclimate cooling. Before these, in the early twentieth century, the only means available to industry were to ensure heat acclimation, high aerobic fitness, to encourage water consumption, and to provide adequate work-rest cycles. The rationale behind this practice is the fact that heat acclimation and euhydration allow for optimal thermoregulation in the human; however, the thermal problems imposed by protective clothing are biophysical rather than biological (21, 23, 28). Therefore, the ultimate solution is to provide a system for the removal of heat from the body surface to the environment since a consideration of the transfer of heat from the body core to the body surface is not the issue when protective clothing is worn. Later, cooling of the entire working environment (macroclimate cooling) was developed with the use of fans and air-conditioners. However, in such cases as outdoor work, mining or space travel, macroclimate cooling is impractical, ineffective, or too expensive, necessitating the study of microclimate cooling systems. Such systems provide the individual with a portable cooling system in direct contact with the skin. While military research on microclimate cooling has focused on the thermal problems presented by NBC clothing, the concepts and knowledge gained from these studies can be applied to any industrial situation in which the worker must be protected from his environment while surrounded by a barrier to heat dissipation.

BACKGROUND

A resting human has a metabolic rate of about 105 watt (W), and can routinely increase his metabolic rate during light exercise. At low ambient temperatures, such heat may be dissipated as needed by the body's thermoregulatory mechanisms of conduction, convection and radiation. Higher ambient temperatures necessitate evaporative cooling as well. Protective clothing impairs these normal cooling mechanisms. Particularly, when the metabolic rate is high the reduced potential for heat dissipation can result in extreme elevations in body temperatures during moderate ambient conditions (secreted sweat soon saturates the air inside the garment, the added vapor cannot adequately permeate the suit and evaporation stops). Likewise, the insulation of the clothing raises the local ambient temperature around the wearer so that it approaches skin temperature and reduces the potential for dry heat exchange.

Microclimate cooling systems using ice-packet vests, circulating cooled air or liquid in tubes over the skin allow improved removal of body heat from the skin and reduce body heat storage. Some of the environmental heat is also absorbed by the system, decreasing the device's effectiveness at very high ambient temperatures. Microclimate cooling systems also facilitate heat loss by maintaining the temperature gradient between the body core and the cooled skin. In fact, maintenance of this gradient is the essential concept behind the use of microclimate cooling because internal heat conduction by blood from the body's core to the periphery for dissipation depends upon this gradient and the resulting cutaneous vasomotor adjustments.

The amount of heat transferred to any microclimate system is dependent on

several factors. The amount and location of body area covered by the device is critical as cutaneous vasomotor adjustments and skin blood flow are not uniform. It is also important to isolate the device from high ambient temperatures to increase effectiveness. Finally, microclimate cooling systems that depend on circulating air or liquid require a power source and connecting tubes to control inlet temperature and flow rate to maximize heat transfer. The length and insulation of these connecting tubes will alter the cooling capacity of the conditioned air or liquid reaching the vest. Each microclimate cooling device has advantages and disadvantages depending on the environment in which it is to be employed.

Montain and colleagues (18) have recently identified another advantage microclimate cooling can provide for persons wearing protective clothing. These investigators found that allowing ~100 $W \cdot m^{-2}$ of cooling over ~12% of the body surface area significantly increased physiological tolerance to heat strain as evidenced by the core temperature when heat exhaustion occurred. They theorized that the cooler skin (~0.4°C) reduced cutaneous venous compliance and increased central blood volume, cardiac filling and mean arterial pressure. Therefore, future research should consider the efficacy of microclimate cooling to both better defend core temperature as well as improve physiological tolerance to heat strain.

In summary, the microclimate cooling studies conducted at USARIEM have investigated the effectiveness of the three different systems (i.e., liquid, ice and air-cooled) through testing which has been performed in the field, in climatic chambers or on a sectional copper manikin, under either or both desert and tropic environmental

conditions. An overview of the work done in each area is presented in the following pages.

LIQUID-COOLED SYSTEMS

The high specific heat of water makes it an ideal medium for microclimate cooling. Cooled liquid circulating in tubes over the skin surface conducts heat away from the body. Heat is also removed from the air around the tubing thereby decreasing the heat received at the skin surface. As the temperature of the water can be maintained at or below the dew point, condensation of moisture around the tubes augments heat loss from the skin as it may be wicked to the semipermeable clothing to enhance evaporative cooling (8).

These aspects of liquid-cooled undergarments (LCU) have been carefully considered and quantified through copper manikin laboratory studies and human chamber and field studies. From the initial prototype LCU (of 40 polyvinylchloride tubes attached to long underwear) developed by the British in 1962, the LCU has undergone multiple design modifications in order to optimize the heat removed while preserving thermal comfort. The prototype liquid microclimate cooling system developed by the U.S. Army Natick, Research, Development and Engineering Center (NATICK) and tested in the following experiment is a vest consisting of three panels constructed of polyurethane coated nylon layers sealed such that the flow channels for the liquid coolant are located within the layers. The vest provides cooling to the torso surface and covers approximately 17% of the total body surface area. Additional panels may

be added to provide cooling to the upper and lower body muscle groups. The vest is attached by an umbilical cord to a refrigeration-control unit that maintains precise control of the temperature and flow rate of the cooling liquid which is usually either water or a mixture of 10% propylene glycol and water.

METHODS

Manikin Studies

Experiment 1

An electrically heated copper manikin was used in this study to evaluate the effectiveness of five LCU over various body surface areas: both the total cooling and the amount of cooling over each individual section were directly measured and electrical power is expressed in watt. The five LCU tested were: a) a water-cooled cap for head cooling; b) a water-cooled vest for torso cooling; c) a water-cooled cap and vest for head and torso cooling; d) a short water-cooled undergarment for upper arms, upper legs and torso cooling, and, e) a long water-cooled undergarment for upper and lower arms, upper and lower legs, head and torso cooling. None of these LCU provided cooling to the hands or feet. The environmental conditions were either 29.4°C, 85% rh, (26°C dp) or 51.7°C, 25% rh, (26°C dp). The heat exchanges in these two hot environments from a nonsweating and also from a maximally sweating manikin surface to the cooling water flowing through the tubing of a LCU were examined. Each of these five LCU were worn with the Combat Vehicle Crewman (CVC) ensemble, and complete NBC clothing minus the overboots. A detailed

description of these methods is provided in a technical report (8).

Experiment 2

The electrically heated copper manikin was used to make a physical evaluation of the effectiveness of four different LCU and a water-cooled cap. The manikin was dressed in a standard hot weather clothing ensemble and the study was conducted in an environmental chamber at air temperatures ranging from 35°C to 49°C. The four LCU included: a+b) 2 garments which provided cooling over the torso-arms-legs (Apollo and British); c) a vest which provided cooling only over the torso and, d) an undergarment consisting of tubing without backing material (Tubing) which provided cooling over all areas except the face. These LCU were operated over a range of cooling inlet water temperatures of 6.7°C to 32°C and water flow rates of 0.7 to 1.8 $\ell \bullet min^{-1}$. The methods employed in this study are provided in greater detail in a technical report (7).

Experiment 3

An electrically heated sectional copper manikin was used to evaluate two portable LCU. The cooling period provided by these LCU is limited by the operating time of the battery supplying power for the pump motor which runs the heat exchanger. One LCU (#1) provided cooling over the torso while the other LCU (#2) provided cooling over the torso and the head. The manikin was dressed in a NBC suit in MOPP IV configuration and cooling rates in watt were determined versus time for a maximally

wet (i.e., sweating) skin condition. Chamber environmental conditions were either 32°C, 56% rh,(23°C dp) or 45°C, 46% rh, (31°C dp). Duplicate tests were made in each of these conditions. A detailed description of these methods is provided in a technical report (11).

Chamber Studies

Experiment 4

Experiment 4 examined the effect of varying the body surface area being cooled by a liquid microclimate cooling system in order to alleviate heat stress associated with the performance of physical work by different muscle groups. Although increasing surface area improves heat loss on a manikin, this may not be necessarily true in humans. In humans, regional heat loss appears to be dependent upon the type of exercise performed (29). For example, for a tank loader who uses upper body muscle groups as opposed to an infantry soldier who uses lower body muscle groups, different patterns of regional cooling may, therefore, be needed. This study was undertaken to determine an optimal configuration for cooling various body surface areas during upper and lower body exercise under heat stress conditions of 38°C, 10% rh, (2°C dp). Subjects were heat acclimated and completed a total of six experimental heat stress tests, each one employing a different combination of exercise mode and regional cooling configuration. Four tests employed coolant chilled to an inlet temperature (T_i) of 20°C and two tests employed T_i of 26°C. The four test combinations at 20°C were: a) upper-body exercise with torso cooling (U-T-20); b) upper-body exercise with torso

and upper-arm cooling (U-TA-20); c) lower-body exercise with torso cooling (L-T-20) and; d) lower-body exercise with torso, upper-arm and thigh cooling (L-TAT-20). Additionally, lower-body exercise at 26°C with: e) torso (L-T-26) and; f) torso, arm and thigh cooling (L-TAT-26) were repeated. All tests consisted of a 150 min exposure (i.e., three repeats of 10 min rest, 40 min exercise) to the hot environment. Exercise entailed either arm cranking or treadmill walking at the same metabolic rate. Subjects were attired in CVC uniform, ballistic armor vest and NBC protective clothing (minus the mask) plus the LCU. A detailed description of these methods is provided in an open literature paper (37).

Experiment 5

This study evaluated two commercial microclimate cooling systems which provide portable liquid cooling. The commercial cooling systems were the ILC Dover and LSSI model vests. Water is utilized as the coolant fluid in the ILC; whereas an aqueous propylene glycol solution is utilized as the coolant in the LSSI system. Both vests operated by circulating their respective coolant fluid from a backpack-mounted heat exchanger (including pump, battery and flow controller) through the liquid garment and back to the heat exchanger. The vests were fabricated from polyurethane coated nylon and had contact cooling surface areas of 0.135 m^2 for the ILC as opposed to 0.184 m^2 for the LSSI (which additionally had a cap with a contact surface area of 0.042 m^2). Subjects were eight male soldiers who were dressed in MOPP IV plus one of the two systems and on eight occasions they attempted to complete a 180 min heat

exposure in a desert (49°C, 20% rh, (20°C dp); 70 W radiant heat load) or a tropic (35°C, 75% rh, (30°C dp)) environment. During the tests, subjects either rested (metabolic rate of 105 W) or performed intermittent treadmill exercise (average metabolic rate of 340 W). The cooling vests were worn under the CVC body armor and were connected via an umbilical line to their backpack unit which was worn over the MOPP IV ensemble. A detailed description of the methods is provided in a technical report (6).

Experiment 6

The effectiveness of a prototype air-liquid hybrid microclimate cooling vest was compared to previously developed air- and liquid-cooled vests to assess heat stress reduction during physical exercise. This hybrid vest is compatible with both air and liquid cooling, and does not necessitate the changing of vests to use the available cooling medium. Five heat acclimated men performed four experiments of 120 minutes of treadmill walking at a metabolic rate of 332 watts in a hot (37.7°C T_{db}, 11.5°C T_{dp}) environment. The vest configurations were air (A) and hybrid-air (HA) both with mean inlet temperatures of 28°C T_{db}, 16°C T_{dp} and flow rates of 4.72 $l\cdot sec^{-1}$ (10 $ft^3\cdot min^{-1}$); liquid (L) and hybrid-liquid (HL) both with mean inlet temperatures of 25°C and flow rates of $6.3\cdot10^{-3}$ $l\cdot sec^{-1}$ (50 $lbm\cdot hr^{-1}$). These vests were worn under MOPP IV protective garments. Endurance time (ET), whole body sweating rate (SR), heart rate (HR), mean weighted skin temperature ($\bar{T}_{sk}$) and rectal temperature (T_{re}) were measured. Subjective assessments of perceived exertion and thermal sensation

were also obtained. A detailed description of these methods is provided in a technical report (5).

Experiment 7

Experiment 7 evaluated three commercial microclimate cooling systems which provide portable liquid cooling. Five heat acclimated subjects attempted three 180 min experiments (three repeats of 10 min rest, 50 min walking at 440 watts) in a 38°C T_{db} and 12°C T_{dp} environment. The subjects wore NBC clothing, MOPP IV configuration, and either ILC Dover Model 19 Cool Vest (ILC), the Life Support Systems, Inc. Cool Head (LSSI) or the Thermacor Technology, Inc. Thermacor Vest (THERM).

The ILC vest consisted of two urethane-coated nylon bladders, worn as panels on the chest and back and provided a potential cooling surface area of 0.17 m^2. The bladders were heat sealed in spots to provide flow channels within each panel. One panel was integrated with a pouch containing a pump and battery holder in addition to a bag which was filled with 1.5 l of water to circulate through the panels. This pouch was worn on the chest by the subjects to facilitate ice refills during the heat stress tests. The water was circulated through the system at an average rate of 2.65 $l \cdot min^{-1}$. Mean inlet temperature of the water was 5.0°C. Testing procedure was that water evolved from melting ice was drained every hour and a new 1.64 kg of ice was placed in the pouch. The battery was replaced every 2 h. The ILC vest could provide a theoretical cooling of 152 W per refill if all the ice evolved to water in 60 min. Total weight of the system as operated was 7.4 kg.

The LSSI vest was also constructed of urethane coated nylon with heat sealed channels for the coolant to flow through. The panels covered chest and back and were connected in series to a cooling cap. The total potential cooling surface area was 0.23 m^2. In the LSSI vest the batteries and coolant reservoir were mounted on a back harness separate from the cooling vest. Cooling was provided by a propylene glycol mixture circulated through the vest and cap and past two 1.0 kg ice canisters at an average flow rate of $4 \cdot 10^{-1}$ $l \cdot min^{-1}$. Mean inlet temperature of the coolant was 14.5°C. Testing procedure was that ice canisters were replaced every 45 min. The batteries were replaced every 2 h. The LSSI vest provided a theoretical cooling of 233 W per set of two ice canisters. Total weight of the system was 7.6 kg.

The THERM vest utilized the heat of vaporization of dichlorotetrafluoroethane (R114) to cool the wearer of a vest covering the chest and back. Pressurized R114 was delivered to 16 hexagonal packets located throughout the vest providing a total cooling surface area of 0.18 m^2. Coolant was provided by a pressurized canister containing 1.34 kg of R114, and belted around the waist separate from the vest. Flow to the vest was controlled by six solenoid valves operated by a small box powered by a 9-volt transistor battery and worn in the front of the vest. Mean evaporative temperature measured at two packets was 28.3°C. The canisters were changed every 20 minutes during the heat stress tests. The THERM vest could theoretically provide 101 W of cooling to the wearer. Total weight of the system as operated was 4.8 kg. A detailed description of these methods are provided in an open literature paper (2).

Field Study

Experiment 8

This study evaluated a LCU for its potential in alleviating the heat stress imposed upon active, heat-acclimated crewmen in a closed hatch, unventilated, stationary XM-1 tank, in the desert. The crewmen wore standard CVC uniform plus various configurations of chemical protective clothing; i.e., MOPP I-IV. All testing was performed in September at Yuma Proving Ground, Arizona between 1330 and 1700 hours. The environmental conditions varied throughout the testing and differed both inside and outside the tank. The temperature averaged 35±1.1°C with 26±2% rh, (14°C dp); winds were from 4 to 13 knots and cloud cover was between 13 and 30%. Throughout the duration of a given heat exposure, each crewman had specific tasks to perform which were done at low to moderate exercise levels. A detailed description of these methods is provided in a technical report (32).

RESULTS

Experiment 1

The range of cooling in watt, provided by each of the five LCU as a function of the cooling water inlet temperature, is presented in Figure 1. These curves show that at cooling water inlet temperatures above 10°C, the water-cooled cap could not provide 100 watt of cooling even for a completely wet skin condition; the water-cooled vest would require a completely wet skin condition; and the water-cooled cap with water-cooled vest could provide 100 watt of cooling even for a dry skin. With the LCU,

short, the skin would have to be completely wet if there was a requirement for it to provide 400 watt of cooling, but the LCU, long, could provide this amount of cooling even if the skin were dry. A "comfortable" cooling water inlet temperature of 20°C should provide 46 watt of cooling using the water-cooled cap; 66 watt using the water-cooled cap with the water-cooled vest; 264 watt using the LCU, short; and 387 watt using the LCU, long. As expected, these results support the conclusion that cooling increases with greater body surface coverage from the LCU and illustrates the importance of biophysical assessments of the heat transfer characteristics concerning prototype microclimate cooling systems using the heated copper manikin.

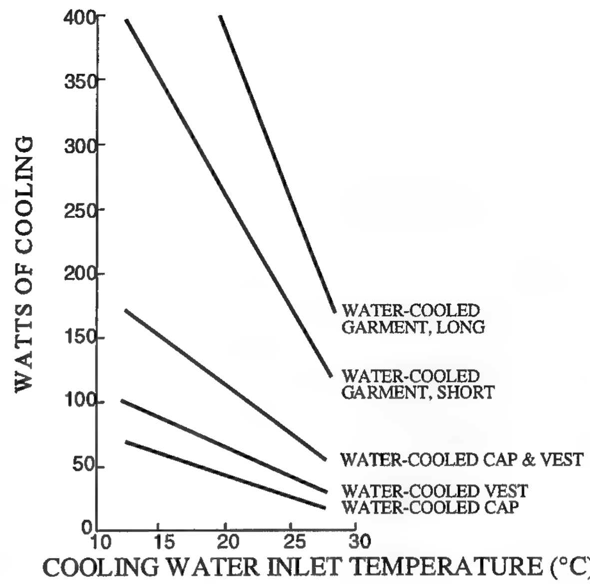

Figure 1. Watt of cooling provided by each of the five water-cooled undergarments plotted against the cooling water inlet temperature for a completely wet (i.e., maximal sweating) skin condition.

Experiment 2

Experiment 2 demonstrates the importance of the proportion of the total skin area covered by a given LCU (and the thickness of this garment) in assessing the effectiveness of the LCU in shielding the body from a hot environment. The findings reveal the Tubing LCU to be most effective in reducing the total amount of heat received by the body from the hot environment; this LCU reduces the total heat gained

by about 70%. The water-cooled vest (covering only the torso) showed the lowest reduction in total heat gain; ~7%. The British LCU reduces the total heat gained by about 38% while the reduction with the Apollo is slightly less at ~30%. When the heat received from a hot environment is restricted to the torso area only, the aforementioned values change to 65% for the Tubing LCU, 50% for the water-cooled vest and 44% for the British and Apollo LCU.

Figure 2 shows the dependence of manikin heat loss on the temperature difference between the manikin surface and the inlet water temperature (T_s - W) and the cooling water flow rate ($\ell \cdot min^{-1}$) of a LCU for these four LCU. These curves show the increase in watt of cooling with increasing skin to water temperature gradient (Part A) and the increase in watt of cooling with increasing water flow rate (Parts B and C). The increase in cooling with increasing T_s - W is dramatic. This increase in cooling is almost directly proportional to the temperature difference; i.e., doubling the temperature difference will

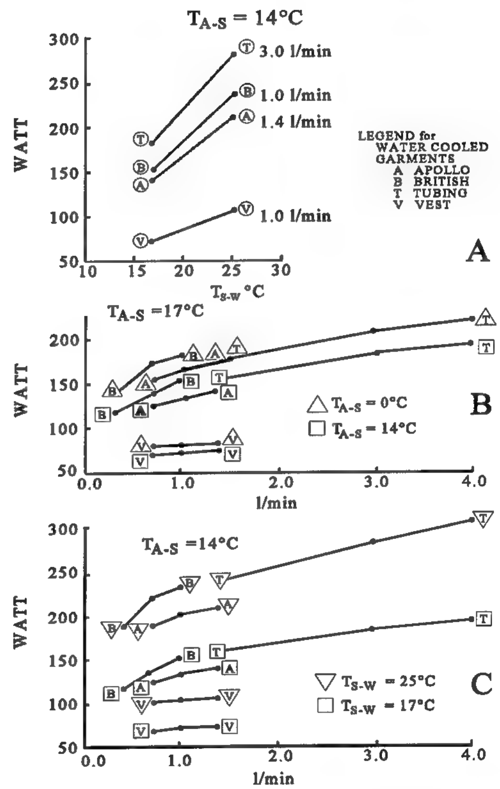

Figure 2. Heat removed (watt) from the sections of the manikin covered by one of the water-cooled undergarments as: (A) a function of the difference between the manikin surface temperature and the cooling water inlet temperature (T_s-w); (B) and (C) as a function of the cooling water flow rate in L/min.

nearly double the heat transfer between a LCU and the manikin surface. In contrast, although cooling increases with increasing water flow rate, this increase in cooling is not directly proportional to water flow rate.

Figure 3 shows that the quantity of cooling provided by the water-cooled cap decreases continuously over time with the steepest decrease occurring after ~90 min of cooling. The addition of an aircrew helmet provides a 30% increase in insulation over the head from the hot environment, and therefore, the benefit of such a practice increases with increasing air temperature. At 47°C and 37% rh, (29°C dp), the total heat removed from the head using this water-cooled cap/helmet system would be about 42 watt (since heat transfer between the head and the cap is increased by up to 13 watt when the helmet is worn). Under these environmental conditions, the quantity of heat removed from the head by the water-cooled cap would equal about 1/3 of the metabolic heat production for a seated person.

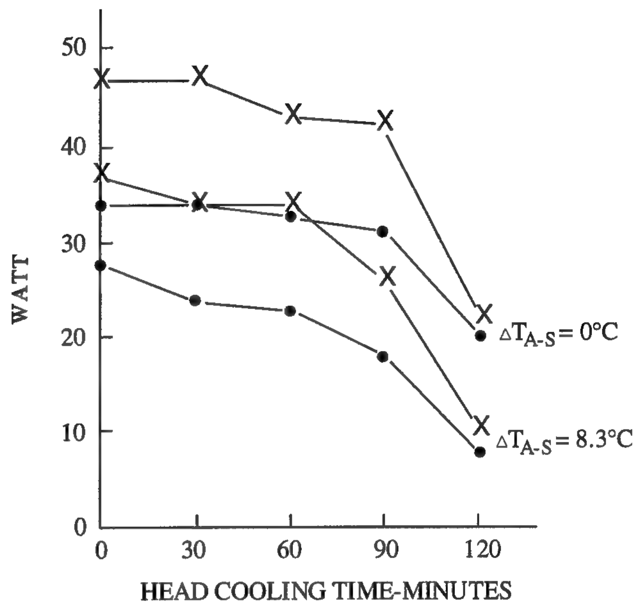

Figure 3. Electrical power (watt) supplied to the head of manikin versus head cooling time in minutes. (•) is data for the water-cooled cap. (X) is data for water-cooled cap/helmet.

These findings, taken in combination with the rates of cooling provided by the LCU against metabolic heat gain demonstrate that whereas these LCU do not

completely isolate the skin surface from gaining heat from a hot environment, they do (in addition to removing internally generated heat) remove one-half or more of the potential for heat gain from the environment. In this manner, the LCU and water-cooled cap are effective measures in alleviating the heat stress of personnel working in the enclosed crew compartments of aircraft or armored vehicles in hot environments.

Experiment 3

The cooling period for the LCU of Experiment 1 is limited by the operating time of the battery, i.e., about two hours. However, battery replacement after two hours of operation apparently did not affect the cooling rate since the curves do not show any abrupt changes in slope after two hours as seen in Figure 4.

Under the conditions of these experiments, there is no leveling off of the cooling rate with time; all curves reach a maximum rate of cooling of 126 to 150 watt (LCU #2 and #1, respectively), then decrease with time as shown in Figure 5. The average torso cooling rate for LCU #1 over the first hour is ~94 watt at 45°C and ~83 watt at 32°C (Fig.4). These

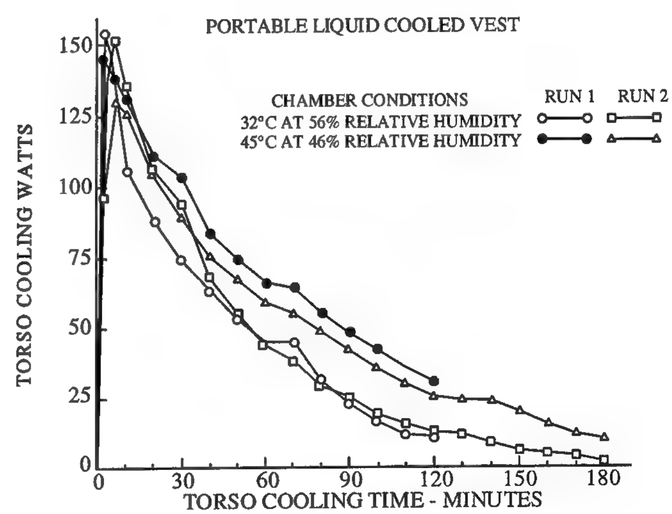

Figure 4. Cooling rates (watt) versus cooling time (minutes) provided over the completely wet (maximal sweating) skin surface area of the torso by the portable liquid-cooled undergarment (LCU) #1.

values decrease to ~46 watt at 45°C and ~26 watt at 32°C over the second hour of cooling. Some torso cooling is provided for up to three hours. The average torso plus head cooling for LCU #2 over the first hour is about 81 watt at 45°C, and 67 watt at 32°C (Fig.5). These values decrease to 67 watt and 43 watt respectively, over the second hour of cooling. As with LCU #1, LCU #2 provides some cooling to the torso and head for up to three hours. Over a two hour cooling period, about 78% of the cooling is provided over the torso and 22% over the head with these percentages being about the same as the percentages of total tubing covering the torso and head, respectively.

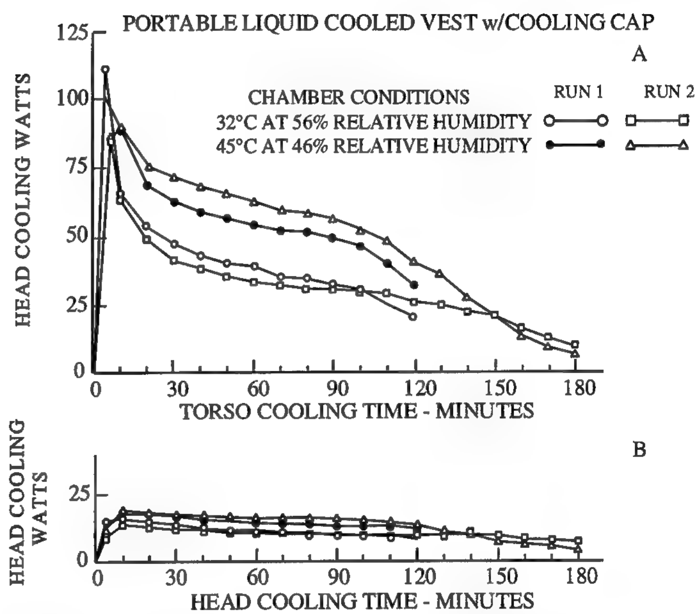

Figure 5. Cooling rates (watt) versus cooling time (minutes) provided over the completely wet (maximal sweating) skin surface areas A. of the torso and B. the head by the portable liquid-cooled undergarment (LCU) #2.

Experiment 4

Figure 6 depicts changes in rectal temperature (T_{re}), relative to the initial value, during each rest/exercise cycle of the two upper-body exercise-heat stress tests of Experiment 4. There were no significant differences between U-T-20 and U-TA-20 in the change in T_{re}. Figure 7 presents pooled data to show the effect of the amount of surface area cooled on changes in T_{re} during lower-body exercise-heat stress tests as there was no

effect of T_i on changes in T_{re} under these conditions. The microclimate cooling system was more effective in alleviating heat stress during lower-body exercise when the surface area for cooling was increased to include the thighs. T_{re} changes as well as heart rates and sweating rates were all lower with torso and thigh cooling when compared to torso-only cooling. This improvement in cooling was probably due to the large increase in amount of active muscle available for conductive heat transfer. A comparison between upper-body (U-T-20) versus lower-body (L-T-20) exercise revealed no difference in metabolic rate, sweating rate, and T_{re} changes. The data from this study indicates that cooling arms in addition to the torso during upper-body exercise provides no thermoregulatory advantage, while

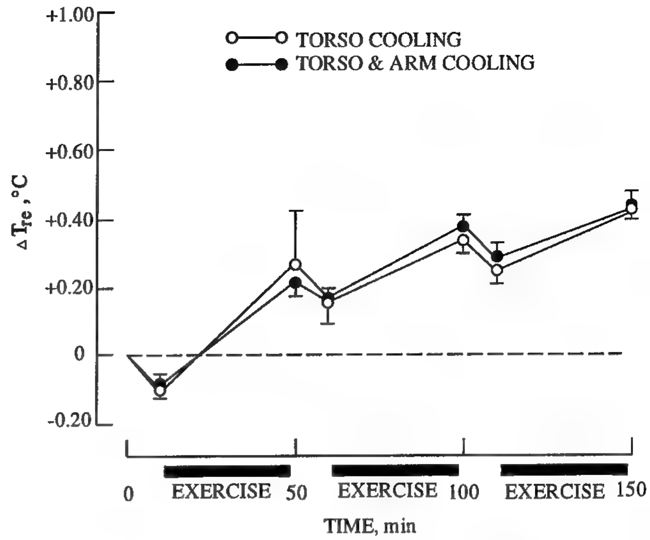

Figure 6. Effect of cooling different skin surface areas on changes in rectal temperature (ΔT_{re}) during rest and upper-body exercise ($\dot{V}O_2$~1.2 $\ell \cdot min^{-1}$[L/min]) under heat stress conditions.

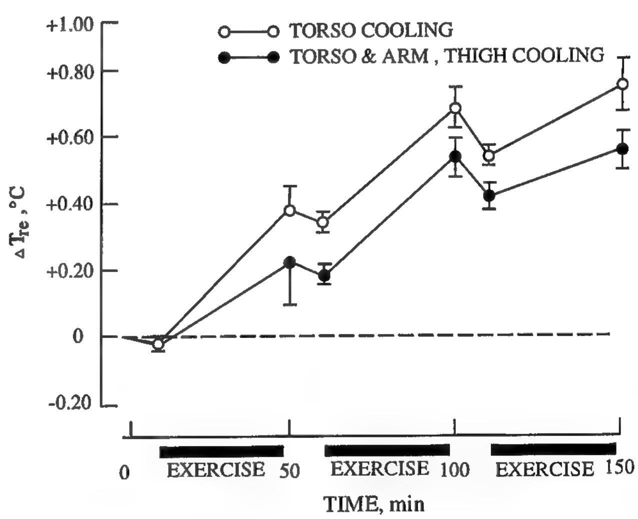

Figure 7. Effect of cooling different skin surface areas on changes in rectal temperature (ΔT_{re}) during lower-body exercise ($\dot{V}O2$~1.2 $\ell \cdot min^{-1}$[L/min]) under heat stress conditions.

cooling the thigh surfaces in addition to the torso during lower-body exercise does provide an advantage.

Experiment 5

For the two commercial cooling systems of Experiment 5, there were no statistical differences ($P>0.05$) between systems in any of the experimental conditions for cooling capacity, endurance time, T_{re}, skin temperature, heart rate, sweating rate or water intake (Figs.8 and 9). All subjects completed the resting tests but were unable to complete the exercise tests in either commercial cooling vest (mean exposure times were 98 and 169 min for the desert and tropic tests, respectively). An excessive amount of maintenance was required to keep the vests operational. A common problem included crimping in the

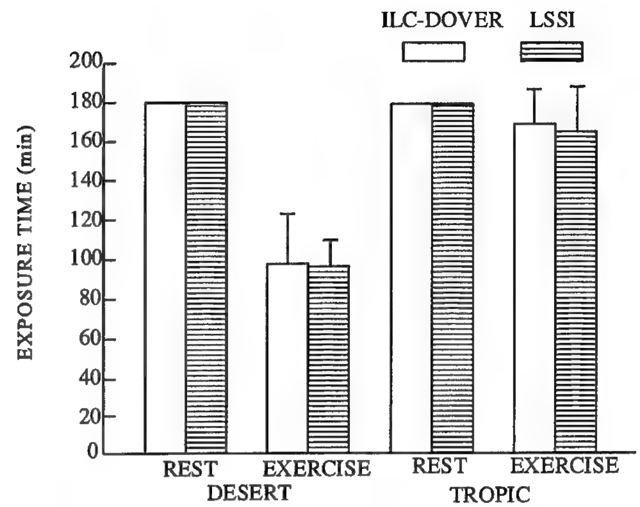

Figure 8. Total exposure time during rest and exercise for two portable commercial cooling systems (desert and tropic).

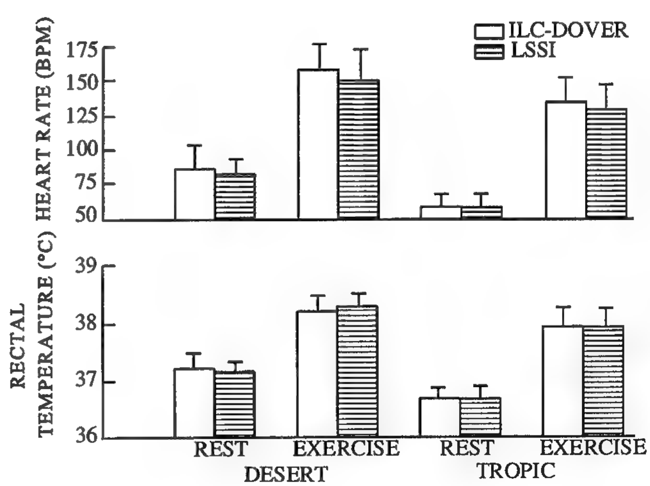

Figure 9. Heat rate and rectal temperature during rest and exercise in desert and tropic experiments involving two portable commercial cooling systems.

vests which would cause the flow to become blocked which in turn resulted in disengagement of the pump. A serious logistical drawback was the improbability of successful utilization of a "buddy" system to maintain the commercial cooling vests. All flow controls and indicators for each system were mounted on the soldier's back so that they were inaccessible to him for regulation and monitoring. Batteries and ice packs would be too difficult for a buddy dressed in MOPP IV inside or outside a tank under battle conditions to change. Finally, the greatest logistical problem was posed by the ice cartridges used in the commercial vests. The maximum cooling that either system could produce would be 180 watt necessitating ice cartridge changes every 20 minutes. Furthermore, this study demonstrates some of the problems encountered in the application of commercially suitable cooling systems to military use.

Experiment 6

All subjects completed the 120 minutes of exercise with all four microclimate cooling vests. There were no differences between vests for either sweating rate, final exercise rectal temperature, or final heart rate. Figure 10 provides the end of exercise rectal temperature responses. Heart rate did increase during exercise (P<0.05) with

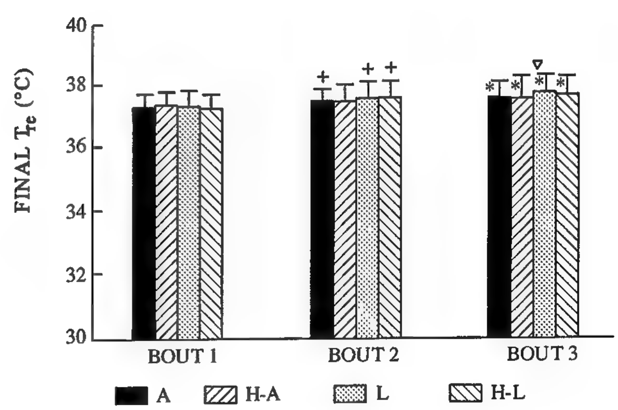

Figure 10. Mean core (rectal) temperatures at the end of each exercise bout with the four microclimate cooling vests: air (A), hybrid air (H-A), liquid (L) and hybrid liquid (H-L) [+Bout 2>Bout 1; *Bout 3>Bout 1; ∇Bout 3>Bout 2 (P<0.05)].

both the liquid and hybrid-liquid vests. Final mean skin temperature with the hybrid-liquid vest was higher ($P<0.05$) than with all other vests, and increase in rectal temperature (rest to final exercise) with the hybrid-liquid vest was greater than with the air vest. There were no differences at any time in the subjective measurements. These data demonstrate that the prototype air-liquid hybrid microclimate cooling vest allowed the same endurance time as the air and liquid vests. However, the small but significantly greater thermal strain shown with the hybrid-liquid configuration relative to the air vest indicates a potential need for an alteration in the amount of cooling provided for the hybrid-liquid configuration, as it had the lowest calculated cooling capacity of all the vests.

Although there were problems with comfort and design in the hybrid vest, in general it compares favorably with both the air vest and the liquid vest in reducing heat strain. However, while subjects were provided sufficient cooling to stay well within safety guidelines, there were some minor differences between vests with the liquid-cooled mode of the hybrid vest showing the weakest performance. Some of these differences may be resolved by changing the liquid flow path in the hybrid vest. Other differences in physiological response between air-cooled and liquid-cooled vests, may possibly be reduced by increasing flow rates of reducing liquid temperature delivered to the liquid-cooled vests.

Experiment 7

The mean, actual cooling rate provided by the vests was calculated to be 244

(±68) W for ILC, 222 (±29) W for LSSI, and 108 (±17) W for THERM, with THERM values being less ($P<0.05$) than the other two systems. An endurance time of 101 min was predicted from a computer model for soldiers wearing MOPP IV and exercising at the same intensity in matched environmental conditions with no microclimate cooling (24). The measured exposure time for subjects with ILC at 178 (±4) min was greater ($P<0.05$) than with both other vests, and exposure time for subjects with THERM at 131 (±47) minutes was greater ($P<0.05$) than with LSSI at 83 (±18) minutes.

The subjects self terminated on all LSSI tests because of headaches. Statistical analyses were performed on data collected at 60 min to have values on all subjects. There were no differences in heart rate, rectal temperature, sweating rate or thermal sensation values among the cooling vests. The subjects' skin temperature was lower ($P<0.05$) for the LSSI than THERM; and rated perceived exertion values were higher ($P<0.05$) for LSSI than the other two vests. Figure 11 shows the regression lines for rectal temperature responses when wearing the three cooling systems. There were no differences in the intercept or slope of lines representing the change in rectal temperature over time when exercising in the three systems.

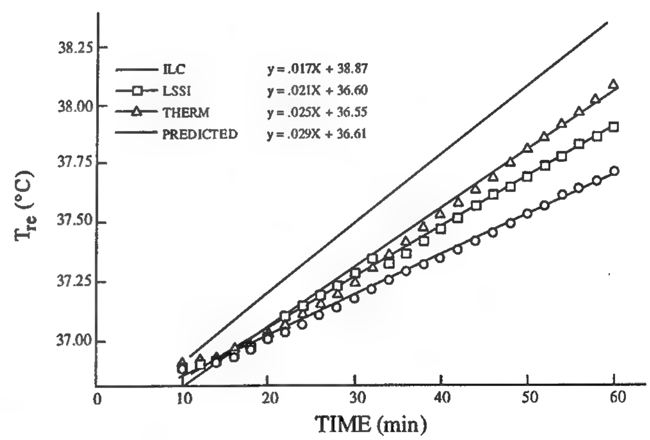

Figure 11. Regression lines of subjects' core temperature change across time while wearing the three microclimate systems and as predicted with no cooling.

In conclusion, there are commercially available microclimate cooling systems to help reduce some heat storage for individuals working in a toxic environment. These systems may have some application to civilian problems requiring brief exposure to toxic agents or in situations where the worker can leave the contaminated site for resupply. However, because of logistical and engineering problems, they do not appear to have much military application. Overall physiological and perceptual results from these experiments indicate that the ILC system provides the best support for the individual working in a hot environment with protective clothing. However, the systems tested can provide cooling sufficient to offset only light to moderate work, and all necessitate a large quantity of supplies for sustained operations. In addition, head cooling resulted in the cessation of exercise because of headaches.

Experiment 8

Figure 12 graphically depicts the contrast in humidity buildup with the closed versus open hatch tank conditions. In the closed hatch condition, although there was not much temperature buildup inside the tank, the interior relative humidity rose dramatically to approach 95% on the sixth day of testing. This rise in

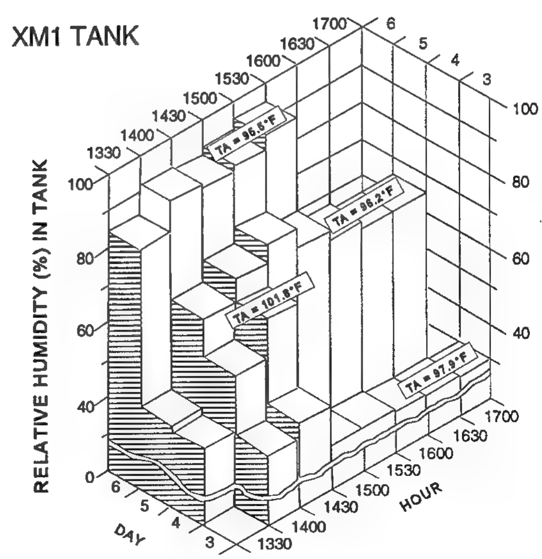

Figure 12. Relative humidity readings inside the XM-1 averaged over each half hour of exposure from days 3-6.

relative humidity inside the tank was the direct result of the crew's sweat production. Also notable is the fact that on Day 4, the interior WBGT rose ~6°C within 45 min: the effects of this heat stress on the crew is evidenced by steeply rising skin temperatures and more slowly responding but nonetheless increasing rectal temperatures of the crew as seen in Figure 13. In contrast, on Day 5 (with essentially similar exposure conditions) when the men wore a water-cooled vest, there was little or no rise in rectal temperature despite the buildup of interior humidity as shown in Figure 14, and skin temperatures were extremely low. The vest removed heat at a rate of about 75 watt from each of the men who were able to complete the full exposure time without difficulty.

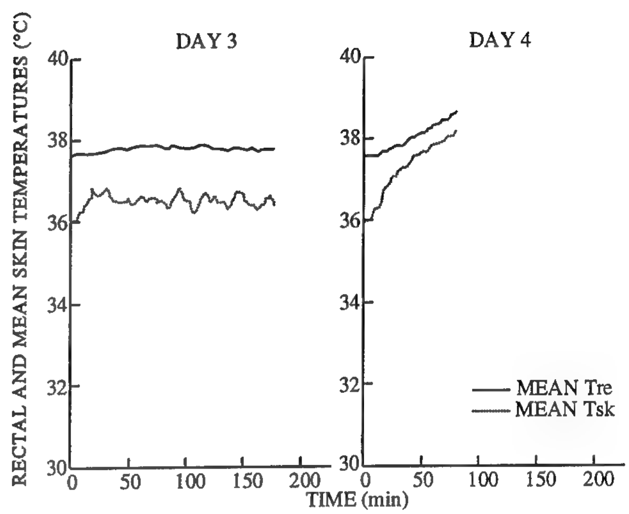

Figure 13. Average rectal temperature (T_{re}) and mean-weighted skin temperature (T_{sk}) of the crew on Days 3 and 4.

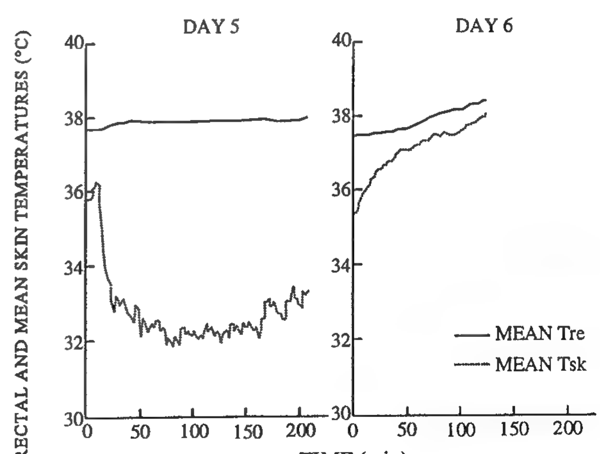

Figure 14. Average rectal temperature (T_{re}) and mean-weighted skin temperature (T_{sk}) of the crew on Days 5 and 6.

The physiological data from this study fully reflects the relative strains of heat exposure when subjects are in MOPP IV gear, and in tanks with closed hatches. The overall study findings are

summarized in Table 1, where average values for skin and rectal temperature, heart rates and sweating rates are presented. Note that sweating rate on Day 4 averages 2.05 $\ell \cdot hr^{-1}$ in contrast to the average 0.63 $\ell \cdot hr^{-1}$ produced when microclimate cooling was available. Clearly there is a reduction in the requirement for drinking water of between 0.9 and 1.4 $\ell \cdot hr^{-1}$ with microclimate cooling. In addition, the mission can be accomplished with microclimate cooling, but it can not be accomplished without it, when the hatches are closed and the ventilating system is off.

TABLE 1

XM-1 Heat stress at Yuma Proving Grounds.
September 1980

DAY	MOPP/ HATCH	T_a		RH		WBGT		TOLERANCE min	T_{sk}	T_{re}	HEART RATE	SWEAT RATE	COMMENTS
		o	I	o	I	o	I				$b \cdot min^{-1}$	$\ell \cdot hr^{-1}$	
1	I/OPEN	38.7°C	39.1°C	39%	31%	31.9°C	30.5°C	>172	35.4°C	37.6°C	92	0.64	TRAIN#1
2	III/OPEN	28.6	31.4	66	60	25.7	26.8	>163	34.9	37.3	76	0.30	TRAIN #2 (CW under)
3	IV/OPEN	37.6	36.6	29	33	30.0	28.1	>177	36.5	37.8	114	0.99	
4	IV/CLOSED	36.0	38.8	30	57	29.9	35.0	(80)	38.3	38.9	162	2.05	T.C. ERRORS <60'
5	IV/CLOSED (w/cooling)	36.1	35.7	25	66	27.4	32.5	>208	32.6	38.1	113	0.63	DOUBLE DRILLS
6	IV/CLOSED	34.4	35.3	29	91	28.9	33.4	(124)	38.1	38.5	147	1.69	T.C. ERRORS ~60'

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ICE-COOLED SYSTEMS

METHODS

Manikin Study

Experiment 1

The electrically heated copper manikin was used to assess the cooling provided by each of two ice packet vests. The manikin was dressed in CVC ensemble, complete NBC protective clothing (minus the overboots) plus ice packet vest. The heat exposures were to three environments: 29°C, 85% rh, (26°C dp); 35°C, 62% rh, (26°C dp); and 52°C, 25% rh, (26°C dp). Cooling rates (watt) versus time were determined for a maximally sweating skin condition. Ice packet vest #1 contained a maximum of 72 ice packets while ice packet vest #2 contained a maximum of 91 packets which presented a continuous interface between ice and torso. The ice packets varied somewhat in size; however, each packet had a contact surface area of ~64 cm^2 and contained ~47 gms of water. One experiment was conducted with fewer than the maximum number of packets that the vest could hold to investigate the effect on torso cooling. A detailed description of these methods is provided in a technical report (9).

RESULTS

Experiment 1

The heat losses from the torso of the manikin equaled the actual watt of cooling supplied to the torso during a given experiment. The decrease in torso watt with torso cooling time for ice packet vest #1 is shown in Figure 15, for each of the hot

environmental exposures. The total heat losses from the torso during each cooling period were: 381 W at 29°C; 362 W at 35°C; 278 W for 52°C; and 187 W at 52°C when 40% of the ice packets were removed from the vest. No cooling is provided when the ice is completely melted and then the torso receives a net heat gain from a hot environment of 52°C, 25% rh, (26°C dp). This heat gain results in skin temperature rising above 35°C.

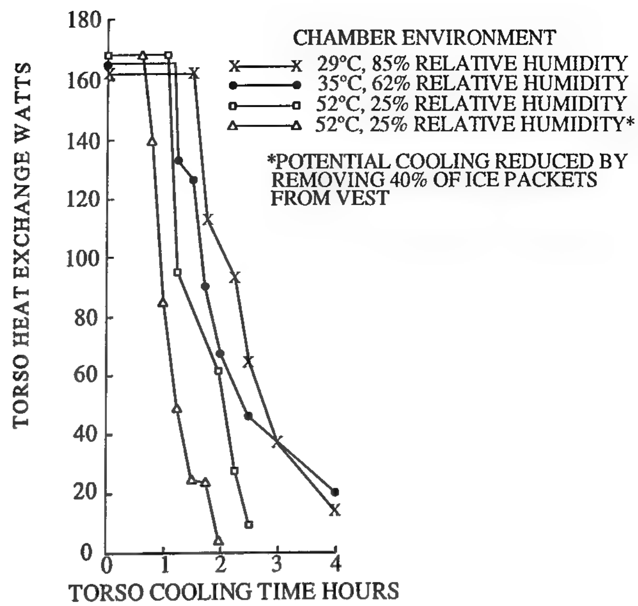

Figure 15. Torso heat exchange (watt) versus torso cooling time (hours) for ice packet vest #1.

Figure 16 shows the decrease in torso watt with cooling time for ice packet vest #2 during exposure to each of the three hot environments. The total heat losses were: 522 W at 29°C; 491 W at 35°C; and 444 W at 52°C. The relationships among these curves are similar to those seen in Figure 15; the effect of increasing the temperature of the environment from 29°C to 52°C is to decrease the torso heat loss

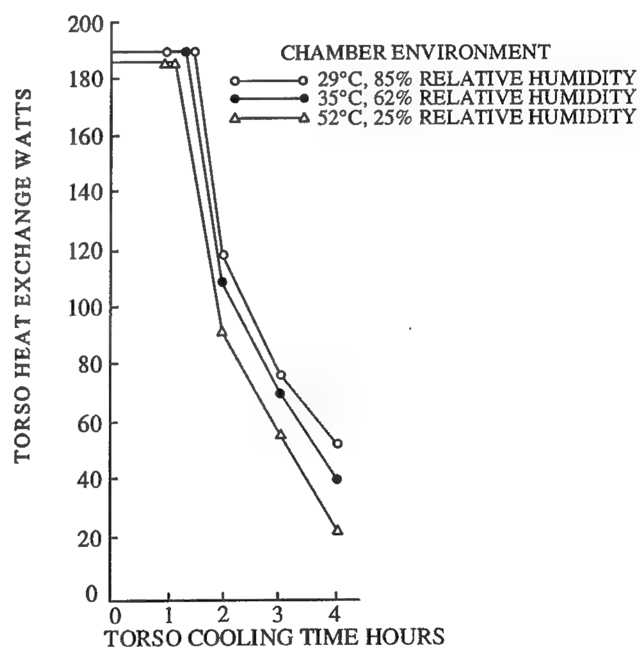

Figure 16. Torso heat exchange (watt) versus torso cooling time (hours) for ice packet vest #2.

by ~50%. The effect of increasing the number of ice packets on the vest by 26% (i.e., from 71 to 91 packets) is to increase both the heat removed from the torso during the cooling period and the length of time during which some benefit would be obtained from the vest. The total heat exchange over a four-hour cooling period when 91 ice packets are attached to a vest are: 760 W at 29°C; 690 W at 35°C; and 370 W at 52°C. Expressed another way, each kilogram of ice which is initially at a temperature of -20°C, has the potential of providing 145 W of cooling to the torso surface and/or a hot environment before the melted ice temperature reaches the average torso skin temperature of 35°C.

The efficiency of cooling provided over a four hour torso cooling period by an ice packet vest (based on the potential cooling provided by a kilogram of ice) is 73% when 91 packets are used with the vest, 69% when 72 packets are used and 63% when 44 packets are used. These approximate calculations indicate that the cooling efficiency of an ice packet vest should increase with the number of ice packets attached to the vest, up to the limit of total torso surface area coverage. Said another way, when ~50% of the torso surface area is covered by ice packets, each additional ice packet added to the vest increases the torso cooling to a greater degree than an ice packet added to a vest with less than 50% torso surface area coverage. Also, with less than full coverage, the cooling is dependent upon the temperature of the hot environment whereas with full coverage, torso cooling over a four hour heat exposure is independent of the temperature of the hot environment. Finally, since ice packet vests do not provide continuous and regulated cooling over an indefinite time period, exposure to a hot

environment would either be time limited, or else involve backup ice packet vests which would require redressing every 2 to 4 hours when the ice in the packets was completely melted and water temperature approached skin temperature.

AIR-COOLED SYSTEMS

METHODS

Manikin Study

Experiment 1

In this study, the electrically heated, sectional copper manikin was used to determine the rates of cooling provided by 3 different air cooled vests (ACV) and a ventilated XM-29 Face Piece. Cooling rates were measured for the sweating and non-sweating skin conditions. The ACV were worn with the CVC ensemble and NBC MOPP IV level clothing in environments that ranged from 29°C and 85% rh, (26°C dp) to 52°C and 25% rh, (26°C dp). Ventilating air flow rates to the vests ranged from 1.5 to 15 cfm while inlet cooling air temperature and rh varied over the range of 10°C, 20% rh, (-12°C dp) to 43°C, 14% rh, (10°C dp). The three ACV were: two NATICK vests which covered only the torso (but cooling air at higher ventilating air flows could travel over the arms and legs) and one commercial model which was fabricated to direct cooling air up the back of the neck and down the back and front of each leg. The NATICK ACV provide torso cooling via a hose/manifold system that is mounted on an open weave fabric. The vest is attached by an umbilical cord to a control unit which precisely maintains the temperature and flow rate of the air being supplied to the vest.

A detailed description of the methods is provided in a technical report (10).

Chamber Studies

Experiment 2

In this experiment, the NATICK ACV was studied to evaluate its effectiveness under severe heat stress conditions. The vest was tested on soldiers working for three hours at a metabolic rate of 340 W under desert conditions of 49°C, 19% rh, (19°C dp), radiant load 70 W, and a wind speed of 1.5 $m \cdot s^{-1}$. The vest was also tested in these environmental conditions without the radiant load at a lower metabolic rate of 240 W for an extended duration of 12 hours. Subjects were heat acclimated and wore CVC uniform, body armor, helmet and NBC MOPP 4 level clothing along with the ACV. The cooling air supplied to the vests was 16°C, 20°C dp. The vest delivered 15 cfm of conditioned air to the chest, neck and back and 3 cfm to the face. A detailed description of these methods is provided in a technical report (26).

Experiment 3

This study determined the effectiveness of the NATICK ACV using selected air temperature and humidity combinations to determine the minimal air conditioning requirements for several military vehicles. Heat acclimated soldiers dressed in CVC uniform and NBC, MOPP IV level clothing attempted 300 min heat exposures (49°C, 20% rh, (20°C dp)) at metabolic rates of 175 and 315 W, each with five different cooling combinations. The 175 W metabolic rate was attained by resting for 45 min and

walking at 1.01 $m \cdot s^{-1}$ for 15 min per hour while 315 W was accomplished by walking at the above speed for 45 min and resting for 15 min per hour. At each of these two metabolic rates, five combinations of temperatures ranging from 20-27°C, 40-58% rh and 7-18°C dp were supplied to an ACV at 15 cfm. During each of the two control tests, the subjects did not wear the ACV; however, the face piece to the mask was ventilated with 3 cfm of ambient air. A detailed description of these methods is provided in an open literature publication (27).

Experiment 4

This study evaluated the effectiveness of the NATICK ACV which was supplied with each of four different combinations of dry bulb and dew point temperatures and air flow rates, to further extend the work done in Experiment 3. Subjects were heat acclimated and exercised at metabolic rates of 175 or 315 W, attempting 300 min exposures on four occasions, while dressed in CVC uniform, Kevlar vest and NBC MOPP IV level clothing. Environmental conditions were constant at 49°C, 20% rh, (20°C dp). Air flow rate to the vest was either 10 or 14.5 cfm. This ACV is designed to provide chest (40%), neck (20%) and back (40%) cooling via a hose and manifold system mounted on an open weave fabric. These methods are provided in detail in a technical report (19).

Experiment 5

The effectiveness of an air shower and the NATICK ACV vest was evaluated in

this study on tank crewmen dressed in CVC uniform with Kevlar (i.e., fragmentation) vest and NBC clothing in MOPP III and IV configurations. The tank was stationary in a climatic chamber with environmental conditions of 33°C, 60% rh, (24°C dp) (WBGT index of 28°C) and minimal wind speed. The crewmen performed standard tank exercises at metabolic rates of 146 to 360 W in the closed hatch tank for 165 min. Cooling was provided by either individual vest cooling to the torso or an "air shower" of 47 cfm to each of the crewmens' areas. One crew also attempted the heat exposure with usage of the M13A1 particulate filter in operation but without microclimate cooling; this exposure was discontinued following the incapacitation of two crewmen within 84 min. Vest cooling supplied about 15 cfm of air distributed to the chest (5-6.5 cfm), neck (2-3 cfm) and back (6.5-7 cfm). Additionally, 3 cfm was supplied to the M25 gas mask. A more detailed description of these methods is provided in a previously published technical report (33).

Experiment 6

Experiment 6 examined the feasibility of using an ambient air microclimate vest-backpack system to reduce thermal strain of soldiers performing physical work in NBC clothing. The experiments were performed in a hot-dry (desert) condition and a hot-wet (tropic) condition which would primarily require insensible and sensible heat exchange with the environment, respectively. Although these environments required different avenues of heat exchange, their magnitude of thermal burden should be similar as they have similar WBGT values of 27.8°C and 28.2°C for the hot/dry and hot/wet

environments, respectively.

Six heat acclimated soldiers attempted four separate 250-min heat exposures while wearing the NATICK Microclimate Conditioning Vest (MCV)-backpack system, combat vehicle crewman uniforms (including body armor) and chemical protective clothing (overgarment, overboots, M25 CB mask/hood, gloves). Environmental conditions were either 35.1°C T_{db} and 19.7° T_{dp} or 40.6° T_{db} and 1.0°C T_{dp} (see Table 2) with an air velocity of 1.1 $m \cdot s^{-1}$. During these tests, the subjects alternated between 50 min of treadmill exercise (metabolic rate ~420 W) and 50 min of seated rest. During the exercise period, the subjects connected their MCV system to the ambient air backpack. During the seated rest periods, conditioned air was supplied to the MCV. It was anticipated that rest periods with conditioned air cooling would enable the subjects to dissipate the heat storage that occurred during the exercise bouts. The environmental conditions and presentation order are outlined in Table 2 . The test conditions were as follows: hot/dry environment--(A) control, (B) 10 cfm, (C) 18 cfm; warm/wet environment--(D) 10 cfm, (E) 18 cfm.

TABLE 2

Microclimate cooling conditions and theoretical cooling provided for test conditions.

Condition	Test Day	Ambient Dry Bulb (°C)	Ambient Dew Point (°C)	Airflow (CFM)	Maximal Evaporative (W)	Maximal Convective (W)	Total Cooling (W)
A	5	40.6	1.0	-	-	-	-
B	4	40.6	1.0	10	256	-20	236
C	3	40.6	1.0	18	571	-43	528
D	2	35.1	19.7	10	173	0	173
E	1	35.1	19.7	18	387	0	387
*Rest	-	22.2	15.0	18	475	106	581

*Conditioned air provided by umbilical to vest during rest periods.

The NATICK vest is designed to provide chest, neck and back cooling via a hose and manifold system mounted on an open weave fabric. The air is distributed through the chest and back manifolds and holes in the hoses at a ratio of approximately 40% to the chest, 20% to the neck and 40% to the back. The ambient air backpack provides a flow (10-18 cfm) of filtered air at ambient temperature for circulating through the vest. The maximal theoretical cooling capacities of the vest when supplied with the different air combinations are shown in Table 2. The backpack is constructed of a fiberglass reinforced ABS molded plastic frame, NBC filter/ABS plastic housing and motor blower. It is powered by rechargeable nickel-cadmium battery packs and weighs 5 kg. A detailed description of the methods is provided in an open literature publication (20).

Experiment 7

A need for microclimate cooling has been established for aviators; and the currently fielded microclimate air-cooled vest (MAV), worn by tank crews in the M1A1 main battle tank, is not compatible with Army aviation equipment. The U.S. Army Natick Research, Development and Engineering Center has developed a prototype microclimate air-cooled vest (PAV) which is designed for aviators and delivers a more diffuse air-flow over the torso than the MAV. The purposes of this study were: 1) to determine if the PAV is as effective as the MAV for providing body cooling; 2) to determine the trade-offs in cooling effectiveness when altering inlet temperatures and air flow rates; and 3) to determine if the more diffuse air-flow to the torso delivered by the PAV will reduce the potential for contact burning when very hot inlet air is provided. In order to address these questions, the following experiments were conducted: 1) to compare physiological responses during exercise in a hot-dry environment between the MAV and the PAV; 2) to evaluate the PAV at several ambient temperatures and flow rates and compare results to control experiments with no cooling; 3) to evaluate the PAV with air flow to the vest at high ambient temperatures to evaluate the potential for contact burning.

Six heat acclimated soldiers attempted twelve (see Tables 3 and 4) heat stress tests each consisting of 180 minute walks at a metabolic rate of approximately 425 watts (treadmill at 1.34 $m \cdot sec^{-1}$, 0% grade). In all HSTs, subjects wore a t-shirt, cooling vest, combat vehicle crewman (CVC) fragmentation protective vest, CVC Nomex coveralls, chemical/biological (CB) overgarment (pants and jacket), M-17 protective

mask, butyl rubber hood, CB butyl rubber gloves with cotton liners and CB butyl rubber overboots.

TABLE 3

Microclimate cooling vest configurations and theoretical cooling provided for the heat stress test in the 45°C, 30% rh environment.

HST	VEST (type)	FLOW ($L \cdot sec^{-1}$)	VEST db (°C)	Vest dp (°C)	MAX COOLING (watts)
1	MAV	7.08	30.0	9.9	680
2	MAV	7.08	40.0	18.8	554
3	PAV	7.08	30.0	9.9	680
4	PAV	7.08	40.0	18.8	554
5	PAV	7.08	45.0	23.3	273
6	PAV	4.72	30.0	9.9	454
7	PAV	4.72	40.0	18.8	369
8	PAV	4.72	45.0	23.3	182
9	CONTROL	0	-	-	0

7.08 $L \cdot sec^{-1}$ = Hi flow
4.72 $L \cdot sec^{-1}$ = Low flow

The PAV was designed to conform with the helicopter crews' equipment. The lap harness worn while flying necessitated moving the umbilical from the front to the side of the vest. The design of the aviators' helmet and placement of shoulder harnesses necessitated removal of the neck hoses, which account for 20% of the air dispersal in the MAV. Additionally, the hard, plastic manifold in the back of the MAV has been removed. The result is a flexible 0.68 kg vest which wraps around the user's

torso and is held in place with a velcro closure and shoulder straps. Unlike the limited, directional air flow from the few openings in the MAV, the prototype vest delivers a diffuse air flow around the torso from many small holes covering the entire inside surface of the vest. A 0.64 cm spacer between the vest surface and user's body allows the air to flow around the torso. This vest also is worn directly over an undershirt. A detailed description of these methods are provided in a technical report (3).

TABLE 4

Microclimate cooling vest configurations and theoretical cooling provided in the 35°C, 70% rh environment.

HST	VEST (type)	FLOW ($L \cdot sec^{-1}$)	VEST db (°C)	VEST dp (°C)	MAX COOLING (watts)
1	PAV	7.08	35.0	28.6	363
2	PAV	4.72	35.0	28.6	242
3	CONTROL	0	-	-	0

7.08 $L \cdot sec^{-1}$ = Hi flow
4.72 $L \cdot sec^{-1}$ = Low flow

Field Study

Experiment 8

This study evaluated the thermal responses of tank crewmen wearing the NATICK air-cooled system (vest and ventilated face piece) while dressed in CVC uniform, Kevlar vest and NBC MOPP IV level clothing. Testing took place in the field in desert (Yuma Proving Ground, Arizona) and tropic (Tropic Test Center, Republic of

Panama) environments. Ambient temperatures during the two desert tests ranged from 23-38°C, 20-64% rh, (1-30°C dp); ambient temperatures during the tropic tests ranged from 27-36°C and 40-81% rh, (13-32°C dp). The crewmen performed continuous operations for up to 12 hours exposure time. The microclimate cooling system provided a total of 20 cfm of conditioned air with each crewman receiving 18 cfm (15 cfm to the vest and 3 cfm to the face piece) with the remainder bulk dumped into the driver's compartment. A technical report (4) describes this system and the methods in detail.

RESULTS

Experiment 1

Cooling rates (watt) for the ACV #1 are given in Table 5 for cooling air flow rates of 6, 8 and 10 cfm. Inlet cooling air temperatures were either 10°C at 20% rh, (-12°C dp) or 21°C at 10% rh, (-12°C dp). Less cooling was obtained in a 29°C environment than under comparable conditions in a 52°C environment. Considering all twelve cooling rates in Table 5, the average percentage of difference in the cooling rates between 29°C and 52°C is about 22%. Without ventilation, the skin (at 35°C) loses heat to the environment at 29°C but gains heat at 52°C. Thus, the potential for change in heat loss (i.e., cooling) is greater at 52°C. Increasing the ventilating air flow rate from 6 to 10 cfm (a 67% increase) increases the cooling rate by ~67%, suggesting that over this air flow range, the cooling rate increases in proportion to the ventilatory air flow rate. The average value of the cooling efficiency of this ACV was 32%; i.e., about

1/3 of the cooling potential of the ventilating air was being utilized. When ACV #1 was worn with the XM-29 Face Piece as shown in Table 6 cooling air to the vest ranged from 3 to 15 cfm and to the inlet of the face piece either 3 or 4.5 cfm. Exposure was in two hot environments: 32°C, 26% rh, (10°C dp) and 49°C, 11% rh, (11°C dp). At the low air flow rate, cooling to the face accounted for ~34% of the total cooling rate with this cooling falling to ~16% at the higher ventilating air flow rates. The efficiency of cooling of the air supplied to the face piece alone was ~18% as compared to ~28% for ACV #1 (vest alone) under these experimental conditions.

Cooling rates for the ACV #2 are given in Table 7 for cooling air flow rates ranging from 1.5 to 10.0 cfm. Inlet cooling air temperatures were either 21°C, 16% rh, (-6°C dp) or 21°C, 60% rh, (13°C dp) in two hot environments of 29°C, 85% rh, (26°C dp) and 52°C, 25% rh, (26°C dp). The cooling curves in Figure 17 show a reduction in the cooling rate with increasing relative humidity of the inlet air. However, for two inlet cooling air conditions of constant temperature but different relative humidity, the cooling efficiency of the one with the initially higher

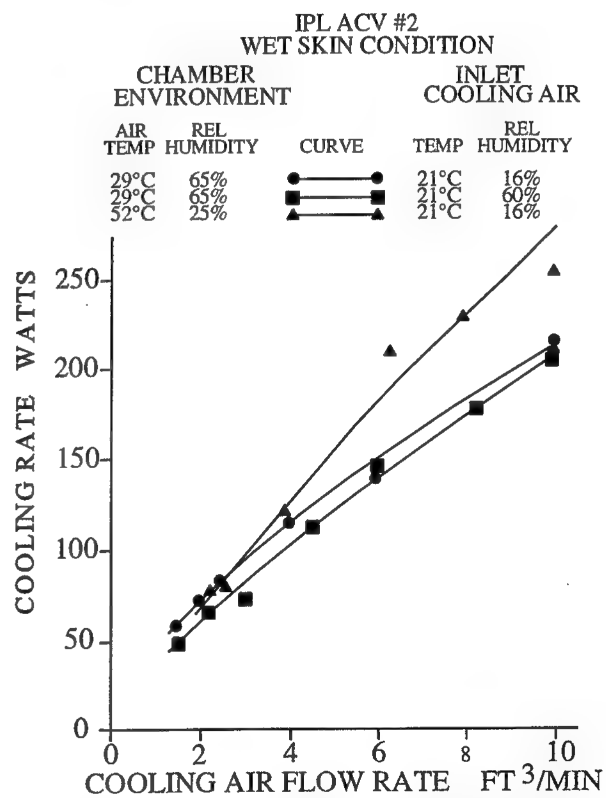

Figure 17. Cooling rates (watt) provided by the IPL ACV #2 over the completely wet (maximal sweating) surface of the torso-arms-legs area as a function of the cooling air flow rate.

relative humidity will always be equal to or greater than the cooling efficiency of the one with the lower relative humidity. When comparing the cooling efficiencies of different ACV, not only the flow rate and temperature of the inlet cooling air have to be the same, but also its relative humidity. At air flows of ~4 cfm or less, the cooling curve for the 52°C environment consistently shows higher cooling rate values than the others above 4 cfm.

This is consistent with the finding for ACV #1. Under the same cooling air flow rate, temperature and relative humidity, cooling provided by air supplied to these vests is greater in the higher air temperature condition; i.e., a given quantity of ventilating air is more efficient. The cooling efficiency of ACV #2 is ~74% for air flow rates of 3 cfm. This is nearly double the cooling efficiency of ACV #1. At these air flows, a decrease in flow rate results in an increase in cooling efficiency. Comparing the cooling rates over the torso-arms-legs in Table 6 for ACV #1 with the cooling rates in Table 8 for ACV #3 shows very little difference at the low ventilating air flows (3 or 6 cfm); i.e., only ~5% difference is noted. At an air flow rate of 10 cfm, the cooling rate for ACV #3 is ~50% greater than the rate for ACV #1. At the higher air flows, both ACVs provided ~55% of their cooling over the torso; however, at these higher flow rates, the contribution of the legs to total cooling increases. The cooling efficiency of ACV #3 is ~31% as compared to 28% for ACV #1 and the face piece is ~18% with ACV #1 as opposed to 22% with ACV #3.

TABLE 5

Cooling rates (watt) provided by the IPL #1 air-cooled vest (completely wet (maximal sweating) skin surface at 35°C).

VENTILATING AIR INLET TEMPERATURE AND RELATIVE HUMIDITY (DB/DP)	FLOW RATE (FT^3/MIN) AIR-COOLED VEST	COOLING RATES (WATT) TORSO-ARMS-LEGS	CHAMBER ENVIRONMENTAL CONDITIONS
10°C at 20% RH* (10.0/-11.8)	6	95 (15.8)**	20°C at 85% RH (29.0/26.3)
10°C at 20% RH (10.0/-11.8)	8	137 (17.1)	20°C at 85% RH (29.0/26.3)
10°C at 20% RH (10.0/-11.8)	10	158 (15.8)	20°C at 85% RH (29.0/26.3)
10°C at 20% RH (10.0/-11.8)	6	122 (20.3)	52°C at 25% RH (52.0/26.2)
10°C at 20% RH (10.0/-11.8)	8	169 (21.1)	52°C at 25% RH (52.0/26.2)
10°C at 20% RH (10.0/-11.8)	10	203 (20.3)	52°C at 25% RH (52.0/26.2)
21°C at 10% RH (21.0/-11.7)	6	82 (13.7)	29°C at 85% RH (29.0/26.3)
21°C at 10% RH (21.0/-11.7)	8	120 (15.0)	29°C at 85% RH (29.0/26.3)
21°C at 10% RH (21.0/-11.7)	10	137 (13.7)	29°C at 85% RH (29.0/26.3)
21°C at 10% RH (21.0/-11.7)	6	103 (17.2)	52°C at 25% RH (52.0/26.2)
21°C at 10% RH (21.0/-11.7)	8	130 (16.2)	52°C at 25% RH (52.0/26.2)
21°C at 10% RH (21.0/-11.7)	10	167 (16.7)	52°C at 25% RH (52.0/26.2)

*Relative Humidity

**Watts/Ft^3/Min

TABLE 6

Cooling rates (watt) provided by the IPL air-cooled vest worn with a cooling air ventilated XM-29 face piece (completely wet (maximal sweating) skin surface at 35°C).

VENTILATING AIR INLET TEMPERATURE AND RELATIVE HUMIDITY (DB/DP)*****		FLOW RATE (FT^3/MIN)		COOLING RATES(WATT)						CHAMBER ENVIRONMENTAL CONDITIONS	
		Air-Cooled VEST	XM-29 FACE PIECE	TORSO-ARM-LEG		HEAD		TOTAL***			
24°C at 41% RH*	(24.0/9.4)	3	3	44	(14.7)****	23	(7.7)****	67	(22.4)****	32°C at 26%RH*	(32.0/9.8)
32°C at 26% RH	(32.0/9.8)	6	NF**	51	(8.5)	0	(0.0)	51	(8.5)	32°C at 26%RH	(32.0/9.8)
32°C at 26% RH	(32.0/9.8)	15	4.5	142	(9.5)	30	(6.7)	172	(16.2)	49°C at 11%RH	(49.0/10.5)
43°C at 14% RH	(43.0/9.7)	10	3	76	(7.6)	15	(5.0)	91	(12.6)	49°C at 11%RH	(49.0/10.5)

*RH
**No Flow
***Sum of cooling provided over Head-Torso-Arm-Legs
****Watt/Ft^3/min
*****DB/DP

TABLE 7

Cooling rates (watt) provided by the IPL ACV #2 (completely wet (maximal sweating) skin surface at 35°C).

			FLOW RATE (FT^3/MIN)	COOLING RATES	
Chamber	29°C at 85%RH*	(29.0/26.32)DB/DP**	1.5	58	(38.7)***
Inlet Cooling Air:	21°C at 16%RH	(21.0/5.7)	2.0	71	(35.5)
			2.5	81	(32.4)
			4.0	119	(29.8)
			6.0	13	(23.0)
			10.0	212	(21.2)
Chamber	29°C at 85%RH	(29.0/26.32)	1.5	49	(32.7)
Inlet Cooling Air:	21°C at 60%RH	(21.0/12.79)	2.2	67	(30.5)
			3.0	72	(24.0)
			4.6	112	(24.3)
			6.0	149	(24.3)
			8.3	177	(21.3)
			10.0	203	(20.3)
Chamber	52°C at 25%RH	(52.0/26.2)	2.2	75	(34.1)
Inlet Cooling Air:	21°C at 16%RH	(21.0/-5.7)	2.6	79	(30.4)
			6.4	209	(32.7)
			8.0	227	(28.4)
			10.0	254	(25.5)

*Relative Humidity
**Dry Bulb/Dew Point
***Watts/Ft^3/min

TABLE 8

Cooling rates (watt) provided by the air-cooled vest #3 worn with a cooling air ventilated XM-29 face piece (completely wet (maximal sweating) skin surface at 35°C).

VENTILATING AIR INLET TEMPERATURE AND RELATIVE HUMIDITY (DB/DP)*****		FLOW RATE (FT^3/MIN)		COOLING RATES(WATT)						CHAMBER ENVIRONMENTAL CONDITIONS	
		Air-Cooled Vest	XM-29 Face Piece	TORSO-ARM-LEG		HEAD		TOTAL***			
24°C at 41% RH*	(24.0/9.4)	3	3	42	(14.0)****	26	(8.7)****	68	(22.7)****	32°C at 26%RH*	(32.0/9.8)
32°C at 26% RH	(32.0/9.8)	6	3	53	(8.8)	39**	(13.0)	92	(21.8)	32°C at 26%RH	(32.0/9.8)
32°C at 26% RH	(32.0/9.8)	15	4.5	159	(10.6)	36	(8.0)	195	(18.6)	49°C at 11%RH	(49.0/10.5)
43°C at 14% RH	(43.0/9.7)	10	3	113	(11.3)	21	(7.0)	134	(18.3)	49°C at 11%RH	(49.0/10.5)

*Relative Humidity
**Hood not worn over head
***Sum of cooling provided over Head-Torso-Arms-Legs
****Watts/Ft^3/min
*****Dry Bulb, Dew Point

Experiment 2

All subjects were able to complete both the 3 and 12 hour heat exposures in Experiment 2. T_{re} during exercise for both tests increased over time ($P<0.05$), T_{re} at the end of the final exercise bout averaged 38.0±0.3°C for the 12 hour test and 38.5±0.6°C for the 3 hour test, representing an average increase of 1.1°C and 1.7°C, respectively, over the initial resting values. In the extreme environment (i.e., 49°C) of those tests, the ACV significantly reduced physiological strain and increased tolerance time to over 12 hours using a 1:1 work to rest ratio.

Experiment 3

All subjects demonstrated a rapid rise in T_{re} during the control test (metabolic rate of 175 W) which involved no ACV but NBC protective clothing, and they were unable to complete the proposed 300 min heat exposure of Experiment 3. Average endurance time was only 118 min. A rapid rate of rise in T_{re} is associated with increased body heat storage and therefore this variable appears to be a good prognosticator of exercise-heat tolerance (24).

In contrast to the T_{re} attained during the control test in this experiment, all five cooling combinations (presented in Table 9) allowed for the maintenance of a near constant body temperature while subjects were dressed in NBC, MOPP IV level protective clothing. Additionally, among the five cooling combinations during the various rest or exercise periods, there were no significant differences in T_{re} responses ($P>0.05$). However, at 315 W, the ACV at all five cooling combinations was less

effective in maintaining T_{re} as illustrated in Figure 18. T_{re} decreased during the rest periods but increased significantly ($P<0.05$) over time with all five cooling combinations. After the fourth exercise bout (~235 min), peak T_{re} averaged 38.0°C for A, 38.2°C for B, 38.3°C for D, 38.5°C for E and 38.6°C for C. Nevertheless, all five combinations were more effective in lessening the rate of rise in T_{re} than the control tests (i.e., no cooling).

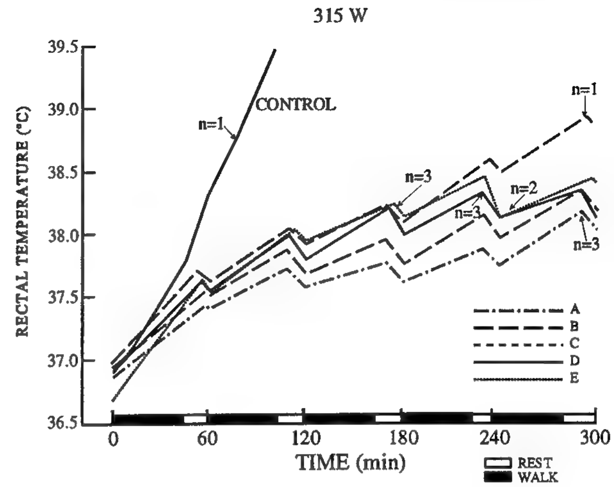

Figure 18. Rectal temperatures plotted across time for the five cooling combinations and the control test at 315W.

TABLE 9

Vest conditions.

CONDITION	TEST DAY	VEST DRY BULB (°C)	VEST DEW POINT (°C)	MAXIMAL EVAPORATIVE (W)	MAXIMAL DRY CONVECTIVE (W)	TOTAL COOLING (W)
A	9-10	20.2	7.2	565	122	687
B	5-6	21.0	12.4	515	116	631
C	1-2	27.0	7.7	555	65	620
D	11-12	27.0	12.9	499	65	564
E	3-4	26.4	18.5	428	70	498
CONTROL	7-8	(VENTILATED FACEPIECE ONLY)				

Figure 19 presents endurance times for each of the five combinations, A, B, C, D and E and for the control tests at 175 and 315 watt. At 175 watt, all subjects were able to complete the 300 minute heat exposure for all five cooling combinations; however, without the cooling vest, endurance time was limited to an average of 118 (±27, SD) min. At 315 watt, endurance times did not differ significantly (P>0.05) among the five combinations (range, 242 - 300 min); however, with no microclimate cooling, the endurance time averaged only 73 (±19, SD) min.

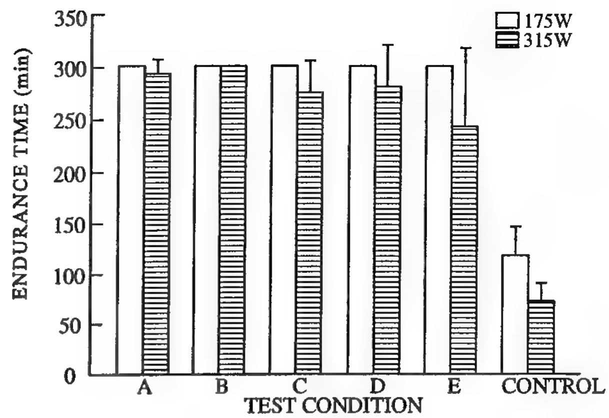

Figure 19. Endurance times (x̄,±SD) at 175W and 315W.

Experiment 4

Table 10 presents the cooling vest test combinations for Experiment 4. Figure 20 graphically depicts the endurance times for the four cooling combination tests. At 175 watt, between vest conditions H and I, there was no significant difference and all six subjects completed the 300 min test in cooling vest H. At 315 watt, again there

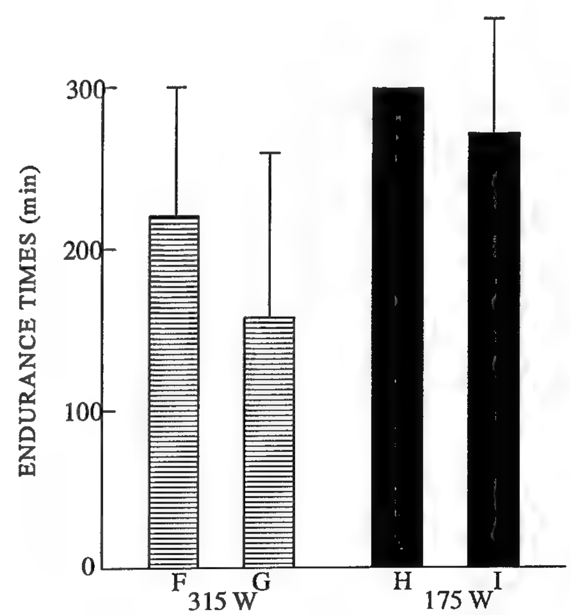

Figure 20. Endurance times (x̄,±SD) for the four cooling vest conditions at 175W and 315W.

was no significant difference between conditions F and G; however, no subject was able to complete the 300 min heat exposure using either vest F or G.

TABLE 10

Cooling vest test combinations.

COMBINATION	TEST DAY	VEST DB/DP (rh) TARGET (°C)	VEST DB/DP (rh) OBTAINED (°C)	AIR FLOW RATE (CFM)	METABOLIC RATE (W)	POTENTIAL COOLING* (W)
F	3	26.7/15.5	26.1/15.6	10	315	196
G	1	29.4/21.1	27.5/21.1	14.5	315	360
H	2	26.7/15.5	22.5/15.5	10	175	218
I	4	29.4/21.2	24.4/21.1	14.5	175	391

*Potential cooling calculated from obtained DB/DP temperatures.

The rectal temperature response at 175 watt for vests H and I is given in Figure 21. After the second walk, T_{re} did not increase significantly (P>0.05) over time with either cooling combination. In contrast, it can be seen from Figure 22, that at 315 watt for vests F and G, T_{re} was higher (P<0.05) at the end of

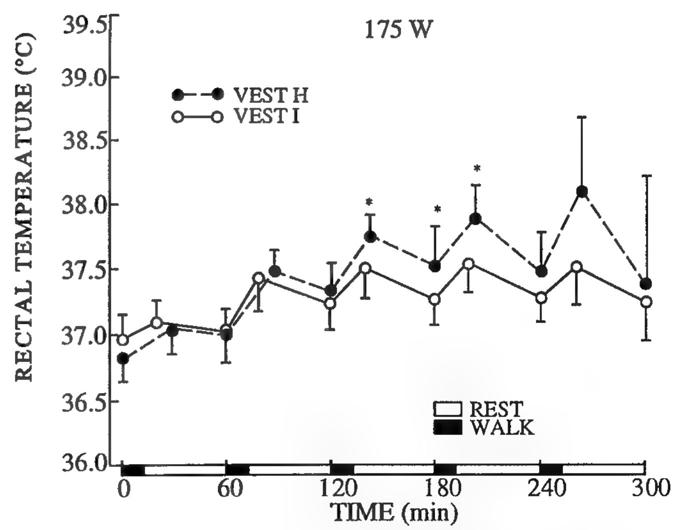

Figure 21. Mean rectal temperatures ($\bar{x}$,±SD) plotted across time for two cooling vest conditions at 175W.

each exercise bout compared to each preceding bout. The average T_{re} exceeded 39.0°C prior to terminating the heat stress for both vest trials.

The air-cooled vest combinations tested in this study reduced but did not prevent body heat storage. Table 11 presents the cooling capacity, mean endurance times and mean rectal temperatures for the control and five vest conditions in Experiment 3 and the four vest combinations of Experiment 4. Vests H and I of Experiment 4 yielded longer endurance times (300±0 and 272±68 min, respectively) which suggests that these combinations of air flow rate and db/dp temperatures were effective in reducing the thermal strain of the subjects. Referring to Table 11, it can be seen that the potential cooling of vest H (218 watt) with the lower air flow rate was ~66% lower than vest A and B from Experiment 3 which had previously demonstrated to be the most physiologically effective in reducing thermal strain. It is possible that at the lower air flow rate (10 cfm), vest H was rendered more efficient by the improvement in heat transfer which was due to the increased transit time across the skin.

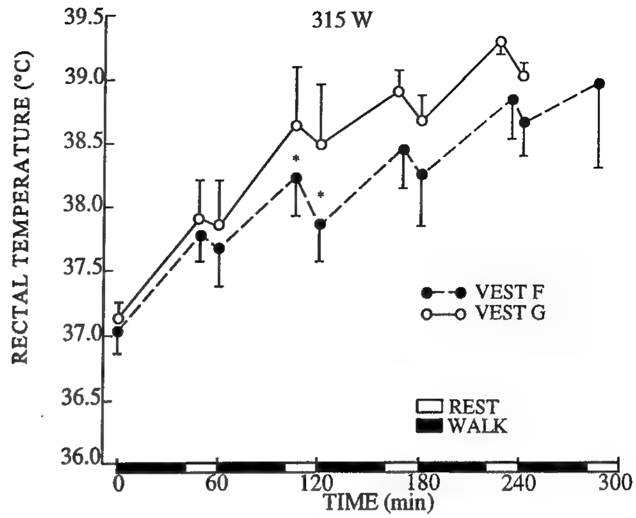

Figure 22. Mean rectal temperatures ($\bar{x}$,±SD) plotted across time for two cooling vest conditions at 315W.

At 315 watt, vest F allowed the longest endurance time, which was 220±78 min. This time is shorter than the previously reported values listed in Table 11, and it was

associated with a greater thermal strain than the prior vest conditions in Experiment 3. In addition, none of the subjects in the present study were able to complete the five hour heat exposures whereas in the aforementioned study, subjects completed the heat exposures 70% of the time. Lastly, use of the microclimate cooling vest combinations F, G, H and I reduced sweating rates which prevented dehydration and the accompanying heat storage due to exercise.

TABLE 11

Comparison of cooling potential, mean endurance times and mean rectal temperatures.

COMBINATION*	POTENTIAL COOLING (W)	175W ENDURANCE (MIN)	175W T_{re}** (°C)	315W ENDURANCE (MIN)	315W T_{re}*** (°C)
CONTROL	---	118	39.0	73	39.4
A	687	300	37.4	293	37.9
B	631	300	37.2	300	38.2
C	620	300	37.6	275	38.6
D	564	300	37.5	281	38.3
E	498	300	37.6	242	38.5
F	196	---	---	220	38.9
G	360	---	---	159	39.3
H	218	300	38.1	---	---
I	391	272	37.5	---	---

* Data for control and combinations A-E from Pimental et al. (27)
**End of walk 5
***End of walk 4

Experiment 5

No differences (P>0.05) were found in tank environmental conditions between

the air shower and vest tests of Experiment 5. Table 12 presents the final physiological responses of the two crews (combined) during these tests. It can be seen that rectal, skin and mean body temperatures and heart rates were statistically higher during the air shower as compared to vest tests. A substantial gradient ($\bar{X}$, 6.3°C; range, 5 to 7°C) was established between the mean skin and rectal temperatures during the vest tests. By contrast, a much smaller gradient between these variables occurred during the air shower test, and these smaller gradients probably contributed to the slight increase in rectal temperatures noted. The heart rate responses are lower during the vest test compared to both the air shower and M13A1 tests: in fact, the final values during the air shower test are statistically higher ($P<0.05$) than the vest test. Finally, total sweat loss values were nearly twice as high during the air shower test as compared to the vest test. This substantiates earlier findings (32) which have demonstrated the benefits of water conservation provided by vest cooling. Therefore, despite the fact that the environmental conditions were substantially improved with the air shower, the combination of insulation and low permeability of the CVC and NBC protective clothing prevented sufficient heat dissipation via this mode (i.e., air shower) to maintain core temperatures.

TABLE 12

Final physiological responses of the crews during vest and air shower microclimate test.

		VEST	AIR SHOWER	DIFF
Rectal Temperature	(°C)	37.2 (0.2)	37.6 (0.5)	0.4*
Mean Skin Temperature	(°C)	30.9 (5.1)	35.7 (1.0)	4.8**
Mean Body Temperature	(°C)	35.1 (0.7)	37.0 (0.5)	1.9**
Heart rate	($b{\cdot}min^{-1}$)	91.0 (16)	112 (28)	21*
Sweat Loss	(liters)	0.64 (.17)	1.29 (.61)	.65**

Values are means (standard deviation); * is P<0.05; ** is P<0.01.

Experiment 6

In the hot/dry environment, the ambient air backpack extended (P<0.05) tolerance time and significantly reduced rectal temperatures, heart rates and sweating rates compared to control; no differences were found between 10 and 18 cfm flow rates. Figure 23 provides the mean peak rectal temperature plotted across time for the control, 10 cfm and 18 cfm MCV backpack experiment. In the hot/wet environment, tolerance time was extended compared to a predicted tolerance time for no microclimate cooling. It is concluded that the ambient air backpack reduced physiological strain and improved tolerance time of combat vehicle crewmen during

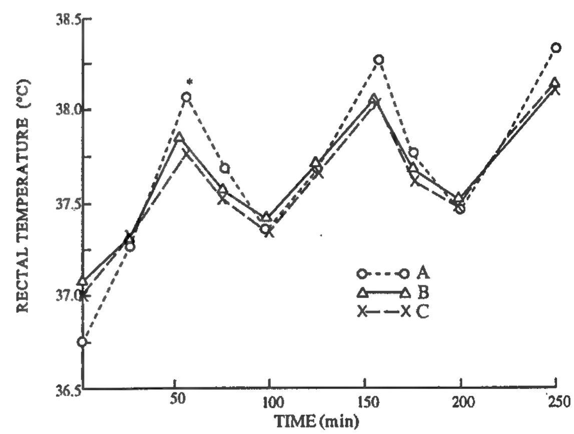

Figure 23. Mean peak rectal temperature plotted across time for (A) control, (B) 10cfm, (C) 18 cfm MCV-backpack tests, hot-dry environment. *indicates P<0.05

exercise in the heat.

Experiment 7

These experiments showed 1) PAV was as effective as MAV in decreasing heat storage at the chosen cooling temperatures and flow rate in the desert environment; 2) conditioned air at 30°C (86°F, 30% rh) to PAV at 7.1 $L{\cdot}sec^{-1}$ prolonged the endurance time threefold for volunteers walking in the desert environment as compared to no cooling (90 min versus 31 min), while the 30°C air at 4.7 $L{\cdot}sec^{-1}$ more than doubled endurance time (72 min), and ambient air to PAV at both flows prolonged endurance time (approximately 50 min versus 35 min) in the tropic environment compared to no cooling; 3) there were no signs or symptoms of contact burning when air was provided to the PAV at ambient desert conditions. Air provided to the vest at 40°C in the desert environment did not improve performance even though calculated cooling at the high flow rate was greater than calculated cooling with 30°C air provided at the low flow rate. It is concluded from these experiments that: 1) the PAV would provide a suitable replacement for the MAV; 2) the PAV could be used at higher ambient temperatures than the MAV; 3) any design changes in vehicle cooling equipment which would necessitate a trade-off between flow rates and temperature regulation should favor lower temperatures over higher flow rates.

Experiment 8

Figure 24 shows the mean T_{re} response of the four tank crewmen during the 12 hour tropic test. During the first hour in the tank, these crewmen displayed a group decrease in T_{re} followed over the next 11 hours by a mean increase in T_{re} of 0.5°C. T_{re} did not approach the physiological safety limit but did show a statistically significant increase ($P<0.05$) over the 12 hour duration time of this test. Mean T_{re} at the start and finish of this tropic test were 37.2±0.05°C and 37.4±0.4°C, respectively. At the low metabolic rates generated in this test, the air-cooled system appears to have helped increase the evaporative cooling capabilities of these subjects during extended operations in the tropics. Similar results were observed during extended operations of 7.5 and 12 hours in desert environments. No significant body heat storage occurred in any of the four tank crewmen during either test. Figure 25 shows that the average rise in T_{re} during the 12 hours was 0.1±0.4°C and during the 7.5 hour test, T_{re} increased by no more than 0.2°C.

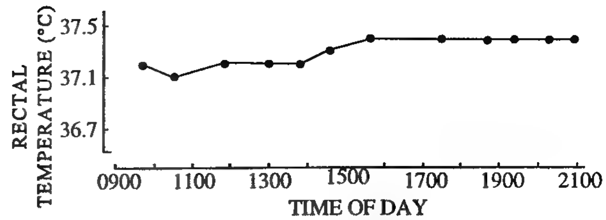

Figure 24. Mean rectal temperature of the tank crewmen during the 12-h tropic test.

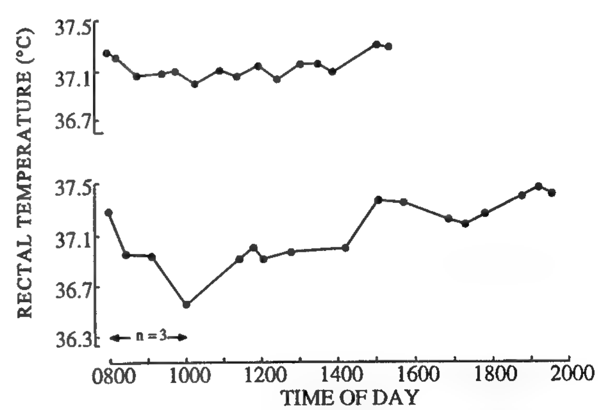

Figure 25. Mean rectal temperature of the tank crewmen during the 7.5 h (top) and 12 h (bottom) desert tests.

DISCUSSION

LIQUID-COOLED SYSTEMS

The amount of cooling provided by a water-cooled garment can be precisely measured on an electrically heated sectional copper manikin. The increase in electric power required to maintain the manikin's surface temperature constant when the water-cooled garment is in place corresponds to the amount of heat transferred to the circulating cooled water. The difference between the total heat removed from the manikin by the water, and the heat transferred to the manikin from the environment, represents the total heat gained or lost. Fonseca has documented (8) that the cooler the inlet water temperature used, the more heat removed. In fact, the rate of cooling provided by a LCU is proportional to the difference between the skin and inlet water temperatures (15). Fonseca also shows that the more body surface area covered by the LCU, the more cooling occurs. Heat transfer is also increased by increasing inlet flow rates but not in direct proportion. Interestingly, more cooling is provided by a LCU when the skin is wet from sweat. A continuous condensation-evaporation cycle is established from the skin to the tubing to the outer clothing potentiating heat loss (8). Cooling inlet water temperatures studied have ranged from 7° to 28°C depending on the garment used. Thermal comfort dictates that cooling inlet water temperatures less than 10°C are unacceptable to the wearer.

Consideration of regional cooling is important when dealing with a water-cooled garment. Cooling to the head with a water-cooled cap, to the torso with a vest and to

the arms and legs using long underwear have been evaluated (8). With the exception of exercising muscles, cutaneous vessels under the LCU may constrict decreasing conductive heat transfer. Placing the LCU over working muscles has been found to be of benefit. Cooling thigh surfaces during leg exercise, in addition to cooling the torso, decreased heat strain in men wearing protective gear more effectively than just torso cooling alone (37). Conduction of heat from the active leg muscles was enhanced by the cooling device. During upper body exercise, however, additional cooling to the arms was not helpful (37), probably due to the regional differences for cutaneous blood flow and volume (29). In subjects exercising on a treadmill while wearing an evenly distributed LCU, heat stress was reduced overall but subjectively the torso felt chilled while the legs remained hot (22). Therefore, depending upon the workplace and activity of the wearer, the LCU can be customized to the type of work and environment.

Portable LCU with the heat sink, battery and pump strapped to the back are available (11), and stationary prototypes with the wearer tethered to the cooling unit by long inlet tubes have been designed (7,8,31,37). All provide continuous and controlled cooling. Problems with the LCU or any microclimate system which uses liquid as a medium are diverse; LCU are heavier than those using air-cooling, adding to the wearer's workload, and interruption of flow, if the tubes are compressed, has also been documented (11). As water has such a high heat capacity, it is ideally suited for microclimate cooling where heat loads greater than 400 watt need to be removed. Conversely, if the cooling requirement decreases, as with decreasing metabolic activity, the wearer can become rapidly chilled causing cutaneous vasoconstriction and

unwanted body heat loss and thermal discomfort (22).

ICE-COOLED SYSTEMS

A study of commercial cooling vests involving the use of ice cartridges was performed in climatic chambers under desert and tropic environmental conditions. Physiological data confirmed that there were no differences between the two commercial vests tested in their ability to reduce thermal strain. Likewise, engineering data concluded that the two vests produced statistically identical cooling capacities. The maximum cooling capacity that could be generated with either system was ~180 watt; however, to offset the metabolic heat loads, typical of many combat scenarios, a microclimate cooling system that will deliver ~350 watt of cooling is required. To put it simply, neither system was sufficient to enable subjects to complete a three hour heat exposure and too much maintenance was required to keep the systems practically operational.

The ideal water-based microclimate cooling system has yet to be developed. However, the concept of providing variable cooling over different regions of the body would allow for optimal cooling. While variable regional cooling would be ideal, particularly in situations of intense physical work, most liquid-based systems are unwieldy, require large amounts of energy and often malfunction in field use (11).

Ice packets of water or dry ice may be positioned on the body, such as in an ice-packet vest under the protective gear, to provide conductive cooling (9). This method of microclimate cooling allows the wearer to move without being tethered or carrying

the cooling unit as is required in other portable systems. No continuous energy source is needed to provide cooling, although a source of refrigeration is necessary. Local skin temperatures of 10-15°C under the ice do not cause undue discomfort (17). Critical aspects of ice-cooling are the actual body surface in contact with the ice at a given time, and the insulation of the ice packets from the environment. As ice melts, its shape changes and its direct contact with the body surface will also change. Consequently, heat is not removed at a constant or controllable rate and is limited to a finite period of time, i.e., until the melting ice reaches body temperature. Once the ice is completely melted, the water temperature continually increases and approaches the temperature of the torso surface. There is no condensation of moisture onto these ice packets from the surrounding air trapped within the clothing layers once the temperature of the plastic ice packets exceeds the dew point of this surrounding air. This is a different experimental condition than when a LCU is worn. The surface of the tubing of a LCU can constantly be maintained at or below the dew point temperature of the surrounding air. Condensation of moisture from the air trapped within the clothing augments the heat loss from the skin surface by continually wicking and blotting this moisture onto the larger surface areas of the clothing. With the ice packet vest, cooling rates are high when the ice first contacts the skin and decrease as the ice melts. Copper manikin studies using environments of 29.4°C, 85% rh, (27°C dp) and 35°C, 62% rh, (26°C dp) documented that ice packet vests worn under the protective clothing provided some cooling for up to four hours. At a higher ambient temperature of 51.7°C, 25% rh (26°C dp), cooling from the vest was negligible after three hours (9). As ice-

based microclimate cooling decreases the rate of heat storage but does not prevent it, this system would be useful for short duration physical work only.

AIR-COOLED SYSTEMS

The essential difference between liquid-cooled and air-cooled microclimate systems is the mechanism of heat transfer employed. While liquid-cooled devices use conduction, air-cooled systems potentiate convective cooling and depend on the evaporation of sweat to be completely effective as a cooling device (30). In air-cooled devices, dry-cool air permeates under the protective clothing and exits after exchanging heat and moisture with the air inside the clothing. The design of an air-cooled vest can increase the efficiency of cooling of the ventilating air by maximizing the proportion of cooling air that diffuses over the surface of the body and minimizing the proportion of cooling air that exits the air-cooled vest directly through the clothing to the hot environment. Maximum cooling to the body has been provided when the ventilating air passes over the skin surface and then exits to the hot environment saturated with moisture at the temperature of the skin. The cooling efficiency in this case would be 100% as opposed to the situation where saturation occurs partly within the clothing layers (rather than strictly along the skin surface) in which case cooling efficiency would be less than 100%. In other words, the cooling air flow rate must be sufficient to ensure that the ventilating air does not reach moisture saturation before it completes its passage over the skin since warm, saturated air will not provide any cooling of surfaces over which it passes (10). By increasing the air flow rate or decreasing the air

temperature, cooling is modulated. In three ACVs studied by Fonseca on the copper manikin, cooling rates increased in proportion to increasing air flow rates and decreasing inlet cooling air temperature (10). These cooling rates were dependent upon the particular hot environment in which the exposure occurred as the ventilating air moving from the surface of the skin outward through the clothing apparently did not provide the thermal isolation from a hot environment that a water-cooled undergarment does.

While air is not as efficient as water due to the difference in specific heat, air-cooled systems are effective in reducing heat strain (27) and in some environments are felt to be as effective as water-cooled devices (30). In addition, air-cooled vests provide drier skin conditions thereby increasing the level of thermal comfort afforded by this system as opposed to that provided by liquid-cooled systems. Soldiers wearing protective clothing, generating metabolic rates of either 175 watt or 315 watt in 49°C, 20% rh, (20°C dp) were unable to tolerate more than 118 min or 73 min of work respectively. Wearing the air-cooled vests, subjects' rectal temperatures, heart rates, and sweating rates were effectively reduced and endurance time extended for both work loads, to 300 min. The vest provided 15 cfm of conditioned air to the chest, neck and back and 3 cfm to the face, with supplied air temperatures ranging from 20-27°C, 40-58% rh (7-18°C dp). While air circulation and heat and heat transfer is not uniform in these devices making some skin surfaces drier than others, cooling is still effective since convective cooling in the drier area does occur.

In environments uncontaminated by biological and/or chemical agents, ambient

air can be employed to circulate under the protective clothing. However, less sweat will be evaporated to provide cooling if ambient humidity is high and local skin irritation results if the ambient humidity is low and the air temperature too hot (30). Cooling of the air just before it enters the clothing is essential as air rapidly warms in long inlet tubes, decreasing maximal cooling. In contaminated environments, compressed fresh air can be provided.

Air-cooled garments are lighter to wear, keep clothing drier and, when face ventilation is also provided, are more comfortable than their water-cooled counterparts. Importantly, air-cooled devices rely on the body's own mechanism for heat loss, i.e. the evaporation of sweat, making excessive body cooling unlikely. Furthermore, they are adequate in removing moderate amounts of generated heat.

CONCLUSIONS

Over the last decade, the Environmental Physiology and Medicine Directorate of our Institute has maintained an active research program evaluating the thermal burden imposed upon men by the wearing of NBC protective clothing ensembles during exercise in the heat (25). Through the use of a life-size sectional copper manikin, measurements have been made of the insulation characteristics (clo) and evaporative impedance (i_m/clo) of these low permeable or impermeable clothing ensembles. The length of time that men could tolerate heat stress under aforementioned conditions has been demonstrated through studies performed in the climatic chambers and the field. Tolerance time has been determined to be more dependent upon impaired heat dissipation than upon the ambient thermal load. To alleviate thermal stress to the individual, therefore, the approach has been to develop a system of microclimate cooling where the microenvironment immediately surrounding the person is cooled versus his macroenvironment (i.e., his working area). A number of prototype microclimate cooling systems involving both air-cooled and liquid-cooled vests have been shown to be effective in alleviating heat stress in soldiers during light exercise while wearing chemical protective clothing in hot-wet and/or hot-dry environments. Studies performed on LCU have revealed the relative importance of the proportion of total skin surface covered by the undergarment not only in providing cooling to the body, but also in shielding the body from heat gain from a hot environment. As the percentage of total body surface area covered by the LCU increases, cooling in watt increases. Furthermore, there is an increase in watt of cooling with increasing skin to

water temperature gradient as well as an increase in watt of cooling with increasing water flow rate. Whereas the LCU studied do not completely isolate the skin surface from gaining heat from the environment, they do remove half or greater of this potential for heat gain. Upper versus lower body exercise was also examined in assessing the effectiveness of LCU to alleviate heat stress during physical work in a hot environment. The findings supported the above conclusion that the proportion of total skin surface covered by a LCU was an important consideration in providing cooling since the LCU was more effective in alleviating heat stress when the surface area for cooling was increased to include the thighs. Lastly, when men wore LCU inside closed hatch, unventilated armored vehicles under desert or tropic environmental conditions, they were able to complete their missions whereas without microclimate cooling they were unable to complete their missions.

Microclimate cooling systems which utilize ice as the cooling medium are not as effective as either liquid or air-cooled systems. Once the ice has completely melted, cooling is no longer provided and the torso receives a net heat gain from the hot environment resulting in skin temperatures in excess of 35°C. The cooling efficiency of one ice packet vest was increased by increasing the number of ice packets attached to the vest (up to the limit of total torso surface area coverage). With less than full coverage, cooling by ice packets was dependent upon the temperature of the hot environment. The logistical problems rendered by ice-cooled systems make them impractical for use as cooling devices in all but very short duration situations.

Since the most important factor affecting thermal strain appears to be the level of

metabolic energy expenditure, when moderate to heavy exercise is performed in hot environments, some soldiers cannot tolerate these conditions for prolonged periods of time even with the inclusion of an ACV; therefore, work/rest periods also need to be employed. At a metabolic rate of 315 W using five selections of air temperature, humidity and air flow rate combinations to an air-cooled vest, cooling was less effective in maintaining a near constant T_{re} (endurance time averaged 73 min) than at a metabolic rate of 175 W (endurance time achieved was 300 min). At low metabolic rates, ACV aid the evaporative cooling capabilities of men during extended (i.e., 7.5 to 12 hours) operations in desert and tropic environments.

ACV provide cooling dependent upon the coordinated interaction of air temperature, relative humidity and air flow rate. In some instances, there is actually an increase in cooling efficiency with lower air flow rates. Heat transfer is improved by prolonging transit time of air across the skin at lower air flow rates, thereby increasing the cooling efficiency of the vest. Furthermore, since ACV are dependent upon the body's ability to evaporate sweat, excessive body cooling by an ACV is unlikely while this has been an inherent problem in LCU.

The Environmental Physiology and Medicine Directorate has developed the ability to predict through the use of modeling, the thermal strain, water requirements, tolerance time and optimal work-rest ratios for soldiers exercising in chemical protective clothing or other low permeable clothing ensembles in a variety of hot environments. The determination of work/rest ratios can be used in conjunction with microclimate

cooling to enable the individual to perform at high metabolic rates while wearing protective clothing in the heat. This comprehensive heat stress prediction model encompasses a series of predictive equations for deep body temperature, heart rate and sweat loss responses for clothed soldiers performing physical exercise at various environmental extremes (24). These modeling efforts have been expanded to include a prototype model for microclimate cooling effects on reducing thermal strain and extending physical work performance. The prototype model assumes that the microclimate cooling vest has 100% efficiency in extracting heat. Figures 26 and 27 provide curves regarding the effectiveness of microclimate cooling to extend physical work to five hours in tropic (35°C T_{db}, 70%rh) and desert (49°C T_{db}, 20%rh) climates, respectively. In both climates, curves are depicted for soldiers wearing NBC clothing while performing physical work at 175, 250,

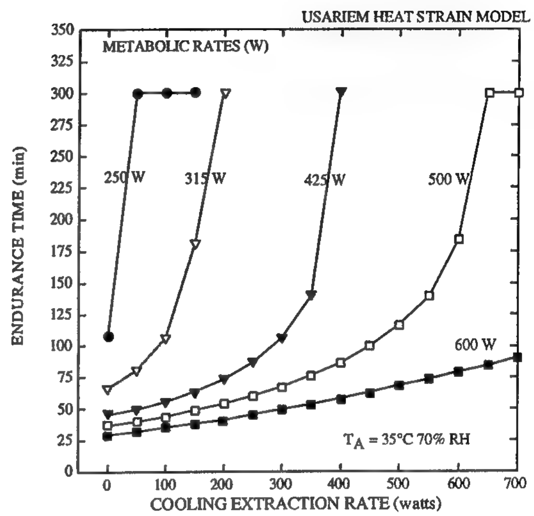

Figure 26. Relationship between microclimate cooling and endurance times at selected metabolic rates when wearing NBC protective clothing in a tropic environment.

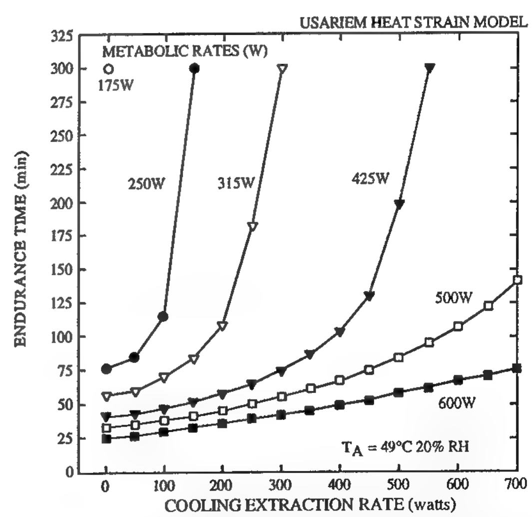

Figure 27. Relationship between microclimate cooling and endurance times at selected metabolic rates when wearing NBC protective clothing in a desert environment.

315, 425, 500 and 600 watts. These metabolic rates represent the range often performed by soldiers for extended periods during military operations. These curves indicate that at heat extraction rates of 300-400 watts, derived from heat balance, microclimate cooling can be a significant force multiplier.

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A REVIEW: US NAVY (NCTRF) EVALUATIONS OF MICROCLIMATE COOLING SYSTEMS

by

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April 1995

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EXECUTIVE SUMMARY

The U.S. Navy Clothing & Textile Research Facility has been involved in the development and testing of microclimate cooling systems (MCS) for Navy applications for several decades. Commercial and prototype systems have demonstrated that MCS significantly reduce heat strain in hot environments. Commercial systems generally require some modification before they can be used on board ship. Passive cooling systems, which are currently available to the Fleet under a commercial item description, have proven most effective for use with general utility clothing for U.S. Navy applications. Preliminary work has been completed to develop new guidelines dictating maximum exposure times for shipboard personnel engaged in routine work in hot engine spaces. Because of problems associated with replenishment, the commercial passive systems are of limited use with encapsulating garments, such as the Navy chemical protective overgarment and firefighter's ensembles. However, physiological tests have shown the benefit of using a passive system when fire fighter's ensemble is worn for short periods of time, such as during a training scenario. Prototype passive systems for extended use with encapsulated clothing have been developed and have significantly reduced heat strain in laboratory tests; further development is required to enhance the reliability of these systems.

A REVIEW: US NAVY (NCTRF) EVALUATIONS OF MICROCLIMATE COOLING SYSTEMS

INTRODUCTION

Heat stress on land and at sea has always been a concern for the Navy. Shipboard heat stress results from the climatic environment, from heat generated within the spaces, especially in engineering spaces, from the work being performed, and from protective clothing. Common methods of dealing with shipboard heat stress include: improvements to shipboard lagging, repair of steam leaks, increased use of air showers, and rotation of personnel based upon the allowable stay times dictated by the Navy's Physiological Heat Exposure Limit (PHEL) curves.

Another method of providing the relief from heat stress is the use of Microclimate Cooling Systems (MCS) which extract heat from the individual through a garment worn close to the skin. There are basically three categories of MCS: passive systems, liquid systems and gas systems. The passive MCS extract heat by conduction through the use of a frozen gel material that is held in the pockets of a torso vest. The liquid MCS operate by circulating a cooling liquid through a torso vest and extracting heat from the body through conduction. The heat is transferred to a cold substance, i.e., a heat sink, by the circulation of the cooling liquid. The commercially available gas-operated systems consist mainly of either air drawn directly from a compressed air source and fed into an air vest or air that has been conditioned (cooled) before being fed into the air vest. Through convection and evaporation, heat is transferred from the body to the air.

HUMAN FIELD STUDIES

Study #1 The Liquid-Air and the Dry-Ice Cooling Systems (Liquid Systems)

Introduction

In August 1980, the Navy Clothing and Textile Research Facility (NCTRF) conducted a field evaluation test of the cooling capabilities of two life-support-suit assembles at the Naval Explosive Ordnance Disposal Technology Center (NAVEODTECHCEN), Indian Head, Maryland (1). The two assembles were:

a. The Liquid Air System (LAS). A self-contained backpack and suit/helmet ensemble which utilized liquid air to provide breathing air and convective cooling to the body and head.

b. The Dry-Ice Cooling System (DICS). A modified suit and helmet similar to (a) above, which was altered to accommodate liquid-cooled long underwear. A dry-ice cooling backpack supplied the chilled coolant to the underwear, which provided conductive cooling to the body and head. This backpack was developed by NCTRF (2).

Test Method

Six volunteers participated in a total of 29 trials, 15 with the DICS and 14 with the LAS, over an 8 day period. The suited volunteer performed typical tasks required of explosive ordnance disposal personnel in emergency conditions, such as walking distances of 2.3 km and 2.9 km. Both walks involved climbing an incline. Both walks occurred on blacktop roads and generally in direct sunlight. The ambient temperatures

were generally in the mid-20°C range in the morning tests and the low-30°C range in the afternoon tests. Oral temperature was measured immediately prior to and after the exercise. Questionnaires were completed daily.

Results

The results indicated that the majority of volunteers preferred the DICS overall and that it provided more effective cooling for a longer period than did the LAS. The average change in oral temperature during exercise was +0.6°C with the LAS, and +0.2°C with the DICS.

Discussion/Conclusions

From the subjective comments of the volunteers, the DICS appeared superior to the LAS suit under moderate to heavy workloads. The change in oral temperature, although relatively small, was significantly greater for the LAS than the DICS and confirmed the subjective findings.

Study #2 Microclimate Cooling Systems: Shipboard Evaluation of Commercial Models

Introduction

NCTRF, under contract to the Navy Science Assistance Program, evaluated the feasibility of using commercial microclimate cooling systems on board ships by conducting an evaluation on the USS LEXINGTON (AVT 16) in the Gulf of Mexico (3).

Test Method

Five commercially available cooling systems from three manufacturers were evaluated. The systems evaluated included: three liquid-cooled MCS - The Life Support Systems, Inc. (LSSI) Cool Head, the LSSI Portapack (LSSIP), and the ILC Dover Cool Vest (ILC); and two air-cooled MCS - the Encon Air System, with (ENCON) and without (AIR) a vortex tube. To provide protection from the possibility of fire, all exterior surfaces of the systems were covered with a fire-retardant fabric.

Both air systems were tethered to a low pressure air line. The LSSIP included a tethered suitcase-like pack which could be picked up and easily moved. The remaining two MCS's were portable, battery-operated, backpack systems. The lightest system was the ambient air system (1.6 kg) while the heaviest system was the LSSI backpack system (7.6 kg).

Twenty nine volunteers were tested in various work spaces which had been identified by ship personnel as having heat stress problems. Sailors were tested during their entire duty shift, normally 4 hours, but in some cases as short as 2 hours. Due to a variety of factors including time constraints, the feasibility of using tethered systems in certain work spaces, and poor performance of the AIR system in early tests, not all subjects tested every cooling system. Each of the systems was tested by at least 13 subjects (except for AIR).

The measurements taken included: dry bulb temperature, wet bulb globe temperature, rectal temperature, skin temperature (3 sites) and heart rate. Cognitive performance was measured with an interactive, computerized, performance

assessment battery. Subjects were periodically asked to rate their thermal sensation on a nine point scale ranging from "very cold" to "very hot."

To determine if the commercial systems could be used onboard ship, we monitored several key logistical items including: air line tether set up, battery usage, ice/canister usage, and operational difficulties.

Results

Due to the unseasonably cold weather, environmental conditions during the course of the evaluation were relatively mild. Overall WBGT averaged 24°C; the range was 16-34°C. Overall dry bulb averaged 31°C; the range was 22-42°C.

Even during the control tests with no cooling, rectal temperatures did not increase by more than 0.2°C over the 4-hour duty shifts. Rectal temperature did not significantly differ between the control test and any of the cooling tests, nor among any of the cooling tests. However, there was a significant difference in chest temperature, which was lowest with the ILC (22.2°C).

For the four tasks included in the performance assessment battery, there were no differences in either speed or accuracy between the control test and cooling tests. On the thermal sensation scale, all cooling systems were rated "slightly cool". Control tests were rated significantly higher ("slightly warm").

Of the 10 subjects who used the LSSI, ILC, Vortex, and LSSIP systems, nine rated the ILC system as their first choice. Overall, the Vortex was the second choice, the LSSI Portapack was third and the LSSI backpack was fourth. Of the 10 subjects

who used only the ILC and the LSSI backpack systems, all of them preferred the ILC. Subjective reasons for the overwhelming preference of ILC Cool Vest included its simple construction, low profile, ease of operation and reliability.

Discussion/Conclusions

Because of the mild environmental conditions during the field test, we could not consider the reduction in heat stress as a primary factor in evaluating the systems. Under hotter conditions, this factor would have been given more significant weight. Based on subjects' overall preference, the ILC system was the overwhelming favorite, with 26 of 29 votes for the number one rating. The reasons stated for the high preference were its low profile, simple operating characteristics, and significant cooling. The least preferred system was the LSSI backpack system. The weight, bulkiness, and interrupted cooling (i.e., operational difficulties) of the LSSI system were reasons for its unpopularity.

HUMAN LABORATORY STUDIES

Study #3 Effectiveness of a Vortex Tube Microclimate Cooling System.

Introduction

A number of shipboard and industrial personnel working in hot spaces have access to compressed air, which can be connected to air-cooled MCS. Air-cooled systems are lightweight and have fewer mechanical components than do liquid-cooled systems. They may, therefore, be advantageous as inexpensive, reliable MCS for shipboard use.

Test Method

NCTRF evaluated the effectiveness of a microclimate cooling vest supplied with compressed air (80 psig) cooled by a vortex tube (4). Seven males attempted heat exposures for 120 min while wearing either a work uniform (clo = 1.1, i_m = 0.6) or a chemical protective ensemble (clo = 1.6, i_m = 0.5). With the work uniform, environmental conditions were 43°C db, 29°C dp; metabolic rate was approximately 425 W. With the protective clothing, conditions were 35°C db, 26°C dp; metabolic rate was approximately 400 W. Volunteers were tested without cooling (CONTROL) and while wearing a vest supplied with 11.5 cfm of cooled air (VORTEX).

Results

All subjects wearing the work uniform (CONTROL and VORTEX) completed the 120 min of exposure. Final rectal temperatures were 39.0 ± 0.3°C for CONTROL and

37.9 $\pm$ 0.2°C for VORTEX ($p<0.05$). Final heart rates were 159 $\pm$ 21 beats per minute for CONTROL and 115 $\pm$ 12 beats per minute for VORTEX. Sweating rates were 700 ($\pm$ 120) and 440 ($\pm$60) g/m^2/h for CONTROL and VORTEX, respectively ($p<0.05$).

With the protective clothing, tolerance times were significantly higher (120 min) for the VORTEX compared to the control tests (103 $\pm$ 18 min). At 90 min, rectal temperatures were significantly higher in the control condition (38.7 $\pm$ 0.2°C) compared to the cooled state (37.4 $\pm$ 0.2°C). Heart rates were also significantly higher with no cooling (148 vs 98 beats per minute for CONTROL and VORTEX, respectively). The average sweating rates of the volunteers when the cooling device was used was significantly lower (220 $\pm$ 80 g/m^2/h) than when there was no air cooling (700 $\pm$ 120 g/m^2/h).

Discussion/ Conclusions

The vortex cooling system has been shown to be effective in reducing heat stress of volunteers wearing both a lightweight and a heavier, protective ensemble. Advantages of a vortex cooler include its low cost, extreme low weight, reliability (few moving parts), and ease of operation. The major disadvantage of the cooler is the fact that an individual must be tethered to a low pressure line. While this may not be problematic for some shipboard applications, such as boiler watch, it may be impractical for many other tasks requiring mobility. Additionally, because of the ever-present danger of fire in an engine space, the tethering could pose a significant safety problem. Quick release, breakaway fittings and/or multiple sites for attaching the air

hose to increase mobility may make the vortex a more feasible option for shipboard use.

Study #4 Microclimate Cooling Systems: A Physiological Evaluation of Two Commercial Systems

Introduction

The Navy Clothing and Textile Research Facility conducted a laboratory evaluation to compare two commercially available liquid microclimate cooling systems for: 1) their effectiveness in reducing heat strain and increasing tolerance time to work in the heat; and 2) their operational characteristics (5). The systems evaluated were the Model 1905 Cool Vest manufactured by ILC Dover, Inc. (ILC), and the Cool Head manufactured by Life Support Systems, Inc. (LSSI). Both are portable, battery-powered, circulating liquid cooling systems. The ILC system includes a torso vest; the LSSI system includes a torso vest and a head cap.

Test Method

Each of nine male volunteers performed a heat test without a cooling system (CONTROL) and with each of the two cooling systems. During each test, volunteers attempted to complete a 3-hour heat exposure in a 43°C dry bulb, 29°C dew point environment (wet bulb globe temperature 36°C). During each heat exposure, subjects wore the Navy utility uniform (clo = 1.1; i_m = 0.6), and walked on a level treadmill at 1.6 m/s (metabolic rate, 360 W).

Results

Only four of the nine subjects were able to complete the CONTROL test. In most cases, use of either of the two cooling systems enabled subjects to complete the 3-hour heat exposures. Rectal temperature responses were similar when either cooling system was used (p>0.05); final rectal temperature averaged 38.1 °C. Changes in rectal temperatures are presented in Figure 1.

The ILC system elicited slightly lower heart rates than the LSSI system, by an average of 7 b/min (p<0.05). Heart rate responses are presented in Figure 2. Total body sweat rates were similar for the two systems and averaged 566 g/m^2/h (p>0.05). Body sweat rates are presented in Figure 3.

The ILC cooling system experienced many fewer operational difficulties and system failures than the LSSI system.

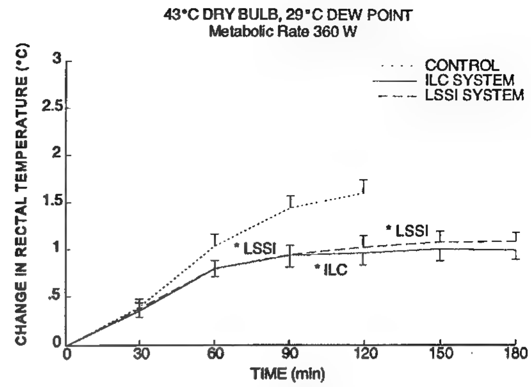

Figure 1. Change in rectal temperature from initial value for the control and cooling tests. T indicates SE; * indicates average time of cooling system ice change.

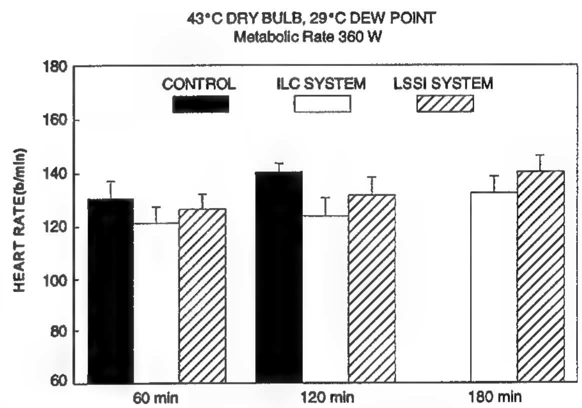

Figure 2. Heart rate at 60, 120 and 180 min for the control and cooling tests. T indicates SE.

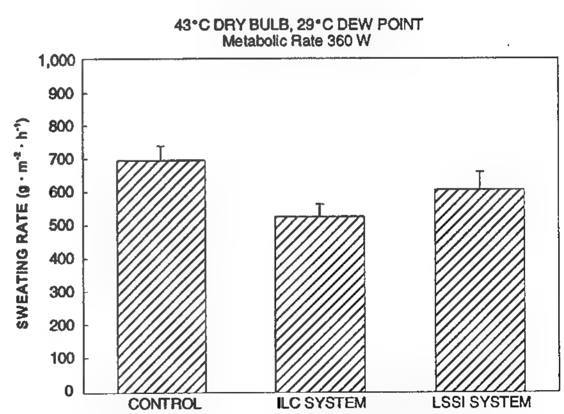

Figure 3. Total body sweating rate for the control and cooling tests. T indicates SE.

Discussion/Conclusions

Under the conditions tested, the ILC Dover Cool Vest and the LSSI Cool Head were similarly effective in reducing physiological strain and increasing tolerance time to work in the heat. Most participants rated the ILC system as cooler, lighter, less bulky, and better overall than the LSSI system. Very few operational difficulties occurred with the ILC system. The LSSI system, however, experienced a significant number of failures and operational difficulties. There is a dramatic cost difference between the two systems: $359 for the ILC Dover Model 1905, compared to $2,376 for the LSSI Cool Head.

Study #5 Effectiveness of Three Portable Cooling Systems in Reducing Heat Stress

Introduction

NCTRF conducted a laboratory evaluation to examine a battery-operated, circulating liquid cooling vest and two "passive", frozen gel pack vests for their effectiveness in reducing heat strain (6). The battery-operated system was the Model 1905 Cool Vest, manufactured by ILC Dover. Inc. (ILC). The passive systems were the SteeleVest, manufactured by Steele, Inc. (STEELE) and the Stay Cool Vest, manufactured by American Vest Co. (AMERICAN).

Test Method

Eight test participants attempted four, 3-hour heat exposures, one without

cooling (CONTROL) and one with each of the three cooling systems (ILC, STEELE, and AMERICAN). During the heat exposures, subjects wore the Navy utility uniform and exercised at 360 W in a 43°C dry bulb, 45% humidity environment.

Results

Of the eight volunteers, only three completed the 3-hour CONTROL test. Six completed the AMERICAN test; all eight completed the ILC and STEELE tests. Two of the cooling systems, the ILC and the STEELE, were similarly effective in reducing heat strain. The third system, the AMERICAN, reduced rectal temperature compared with the CONTROL, but not skin temperature, heart rate or sweat rate. Figures 4, 5, 6, and 7 present data on change in rectal temperature, mean weighted skin temperature, heart rate and sweating rate respectively.

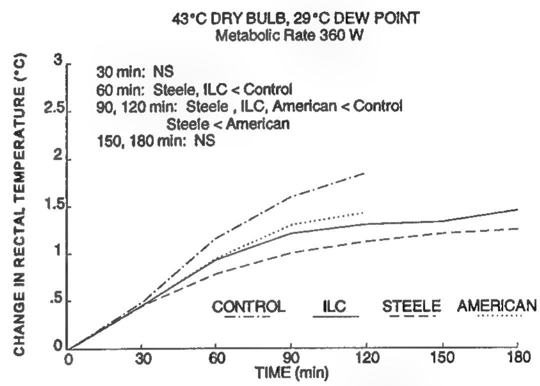

Figure 4. Change in rectal temperature from initial value for the control and cooling tests.

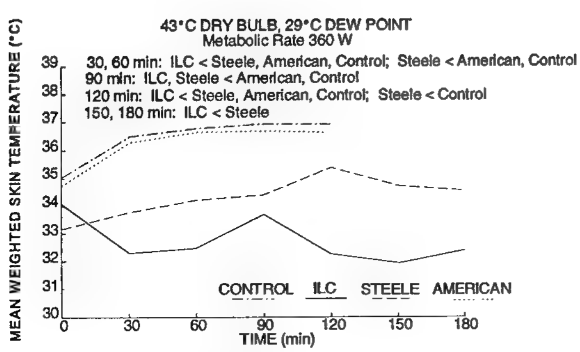

Figure 5. Mean weighted skin temperature for the control and cooling tests.

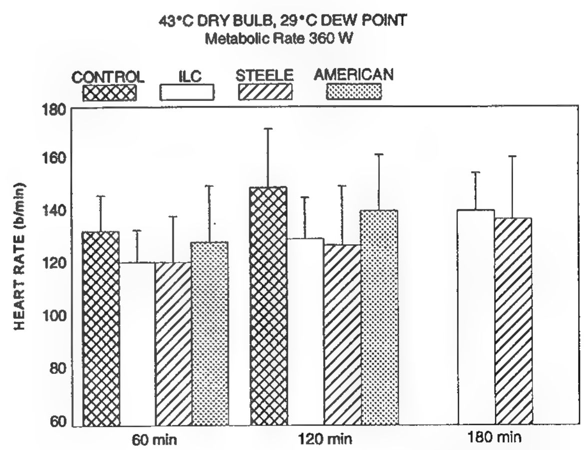

Figure 6. Heart rate at 60, 120 and 180 minutes for the control and cooling tests. T indicates SD.

Discussion/Conclusions

Two of the three portable cooling systems tested in this evaluation - the ILC Dover Cool Vest and the Steele, Inc. SteeleVest - were similarly effective in reducing thermal strain when used by volunteers exercising in a 43°C, 45% rh environment. The third cooling system - the American Vest Stay Cool Vest - reduced body core temperature compared to no cooling, but was not nearly as effective as the other two systems.

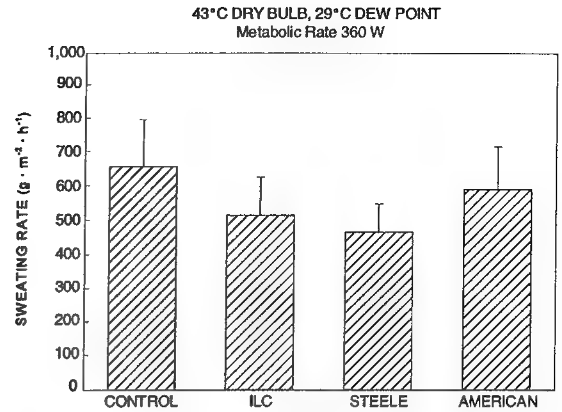

Figure 7. Total body sweating rate for the control and cooling tests. T indicates SD.

The surface area available for cooling in the ILC vest (1710 cm^2) is only 62% of that in the Steele vest (2761 cm^2); however, in this evaluation, chest temperatures with the ILC system were 6°C lower than the Steele. This may be because the ILC's design allows for better contact of the vest to the body, and there is very little insulation between the body and the circulating liquid. The net result was that, despite a large difference in surface areas, the ILC and the SteeleVest were similarly effective in reducing heat stress.

The poor results of the American cooling system in reducing heat strain may be due to two reasons. First, the surface area available for cooling in the American vest is only 81% of that in the ILC and 50% of that in the Steele. Second, the American vest cannot be tightened to make good contact between the body and the gel packs;

evidence for this was seen in the high chest temperatures measured even when the gel packs were completely frozen.

While both the ILC Dover Cool Vest and the SteeleVest were effective in reducing heat strain, with either system there are logistical concerns which must be addressed for shipboard use. When adjusted for duration between coolant changes, the SteeleVest used 70% more coolant by weight and approximately 20% more coolant by volume than the ILC. In that respect, the ILC may be considered a more efficient cooling system than the Steele. Because of its mechanical nature, however, the ILC may require more maintenance than the passive cooling system. The ILC batteries require storage space and must be recharged for a minimum of 8 hours after every 2-3 hours of use. Ship's personnel must evaluate the logistical burdens of the additional freezer capability required by the SteeleVest and the maintenance and battery support required by the ILC.

Study #6 -Effectiveness of a Prototype Microclimate Cooling System for Use with Chemical Protective Clothing

Introduction

NCTRF conducted a laboratory evaluation to determine the effectiveness of a prototype, portable microclimate cooling system (MCS) designed by NCTRF for use with chemical protective clothing (7). The U.S. Navy has two configurations of chemical protective clothing: the chemical protective overgarment (Mark III) and the Mark III worn with the Navy Wet Weather ensemble. The Mark III is a semi-permeable,

two-piece garment (trousers and smock with attached hood), with a clo value of 2.0 and an i_m value of 0.42 measured at 0.3 m/s wind velocity. Under conditions of potential liquid chemical contamination or exposure to ocean spray, the Navy Wet Weather ensemble may be worn over the Mark III, thereby making the clothing ensemble impermeable. The Wet Weather ensemble consists of bib front overalls and a parka constructed of cholorprene-coated nylon twill. The clo and i_m values of the Wet Weather ensemble worn over the utility uniform and Mark III are 2.4 and 0.24, respectively.

The purpose of this evaluation was to determine the effectiveness of the prototype circulating liquid MCS in reducing physiological strain of volunteers working in the heat while wearing the Navy chemical protective ensembles.

Test Method

The MCS circulates chilled liquid through a torso vest. A backpack unit contains an ice pack. A pump and motor assembly and a rechargeable battery are mounted on a chest or waist strap. Total weight of the MCS is 9.3 kg. To examine the effectiveness of the system in reducing heat strain, seven male test volunteers participated in a laboratory heat stress evaluation.

The volunteers attempted 120-min heat exposures in a 35°C, 60% humidity environment while exercising at a time-weighted rate of approximately 300 watts. They were tested four times: with and without the MCS while they wore the semi-permeable and the impermeable chemical protective ensemble.

Results

Exposure time in all cases was 120 min, except when the impermeable ensemble was worn without the MCS (mean tolerance time = 96 min). Use of the MCS significantly reduced rectal temperature by an average of 0.5°C after 120 min with the semi-impermeable ensemble and by 1.3°C after 100 min with the impermeable ensemble. Mean weighted skin temperature was significantly lower by an average of 3.3°C when the MCS was used. Rectal temperature and mean weighted skin temperature data are presented in Figures 8 and 9, respectively.

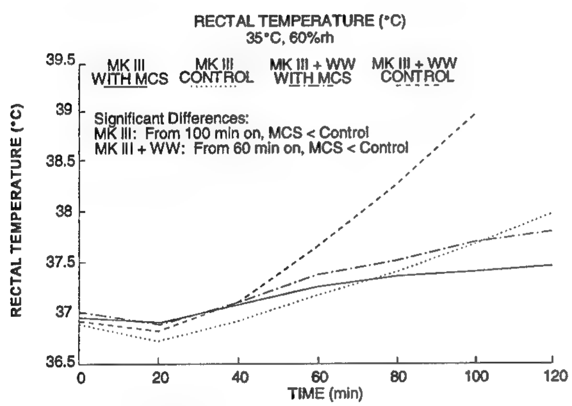

Figure 8. Rectal temperature responses with and without the cooling system.

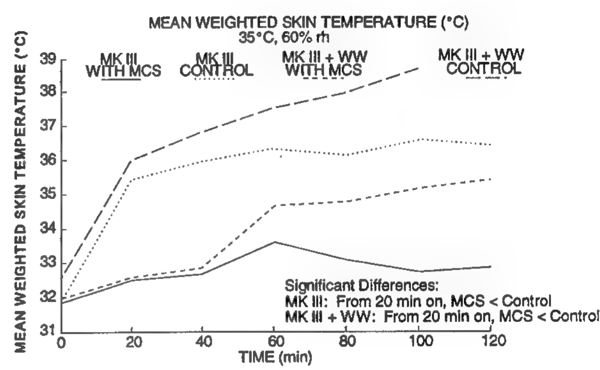

Figure 9. Mean weighted skin temperatures with and without the cooling system.

As seen in Figure 10, use of the MCS significantly reduced heart rate by 30 and 42 b/min with the semi-impermeable and impermeable ensembles, respectively. Sweating rate was also significantly reduced, by an average of 37% (Figure 11).

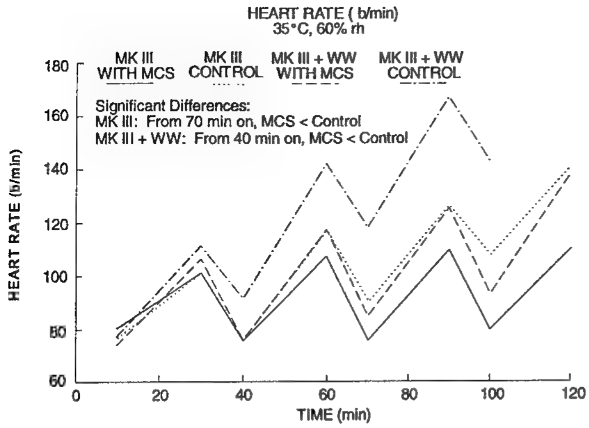

Figure 10. Heart rate responses with and without the cooling system.

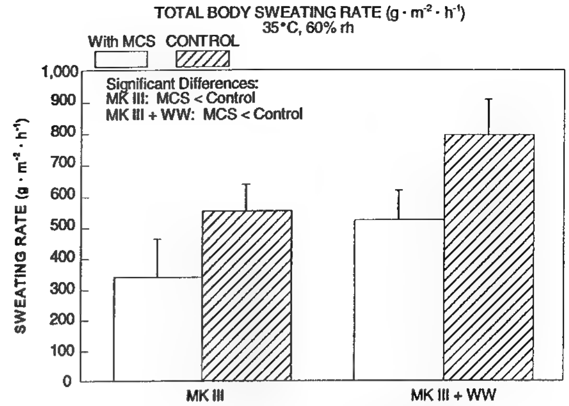

Figure 11. Total body sweating rates with and without the cooling system. T indicates SD.

Discussion/Conclusions

The prototype MCS was effective in alleviating heat strain and enabled volunteers wearing chemical protective clothing to complete a 2-hour heat exposure in a 35°C environment. As currently designed, however, the system is not operationally reliable or rugged enough for near-term Navy use. Further development and/or modifications to the prototype system are required.

Study #7 -Effectiveness of a Selected Microclimate Cooling System in Increasing Tolerance Time to Work in the Heat - Application to Navy Physiological Heat Exposure Limits (PHEL) Curve V

Introduction

On board U.S. Navy ships, whenever dry bulb temperature in a work space exceeds 38°C, or under conditions of "unusually high heat or moisture" or "arduous work", wet bulb globe temperature (WBGT) is measured. The WBGT is then applied to

a series of Physiological Heat Exposure Limits (PHEL) curves (8). The PHEL curve chart consists of six curves (I-VI), each of which represents a different time-weighted metabolic rate ranging from 177 to 293 W. For all curves, it is assumed that the Navy utility uniform or work coverall is worn. Based on the work rate and the WBGT, the PHEL curves establish maximum safe exposure times for shipboard personnel. If the scheduled duration of a duty period exceeds the safe exposure time established by the curve, personnel must be rotated out of the heat stress area and given prescribed recovery periods. The PHEL curves are strictly adhered to onboard ship; only under operational emergencies may the ships Commanding Officer waive the curves.

Previous research has shown that various types of microclimate cooling systems - including dry ice, liquid, gas and passive systems - can be used to reduce heat strain and increase tolerance time to work in the heat (e.g. 1,4,5,6,7). Due in large part to the results of these studies, a number of passive MCSs were used on U.S. Navy ships in the Persian Gulf during the summer of 1988 and were favorably received.

The Navy's widespread use of MCS on board ships will partly depend on the development of a table of recommended safe exposure times which will reflect the increased tolerance times when the MCSs are used. If stay times and/or work efficiency cannot be significantly increased by the use of a cooling system, it is doubtful that the Navy will incur the expense of these systems "merely" to increase personal comfort.

The primary purpose of this evaluation, therefore, was to begin evaluating the increases in tolerance time when a selected microclimate cooling system - the

SteeleVest - is used in various environments (8). In this evaluation, one metabolic rate (272 W) was used, which corresponded to PHEL Curve V (the second highest of the six work rates represented by the PHEL curves). Five environments were examined, encompassing WBGT conditions ranging from 36-39°C. Although the WBGT range was small, dry bulb temperatures ranged from 38-49°C, and humidity 25-80%. Because of this, it was expected that within this relatively small WBGT range, there might be large differences in tolerance time with the cooling vest. Some of the tested environments were chosen to simulate environmental conditions typical of ships operating on the Atlantic Coast during the summer months. Under these combinations of WBGT and work rate, the current PHEL curves limit exposure time to 60-95 minutes.

The secondary purpose of the evaluation was to compare thermal responses and tolerance times in equivalent WBGT environments. Maximum exposure times established by the PHEL curves are the same for environments having equivalent WBGT. Some research, however, has shown that physiological responses to equivalent WBGT conditions are not necessarily equivalent, particularly when hot-humid and hot-dry environments are compared. Under the test design, therefore, we chose humid and dry environments that produced equivalent WBGT.

Test Method

The SteeleVest has six pockets (three in front, three in back) which hold 0.8 kg frozen gel packs, consisting of a cornstarch and water mixture. The vest has a cotton canvas shell and the pockets are externally insulated with Thinsulate. The total weight

of the system is 5.1 kg. The vest comes in one size only.

Eight heat acclimated, healthy male volunteers participated in the evaluation, which consisted of 10 tests - with and without the cooling vest in five different environments (repeated measures design with each participant serving as his own control). The five environments are listed below. The designation for each environment denotes the WBGT (°C) and "H" for the more humid, and "D" for the drier of the two equivalent WBGT environments.

Dry Bulb	rh	WBGT	Designation
38°C	80%	36°C	WBGT36H
49°C	25%	36°C	WBGT36D
43°C	60%	38°C	WBGT38H
49°C	35%	38°C	WBGT38D
49°C	39%	39°C	WBGT39

Wind velocity was 1.0 m/s

Volunteers attempted to complete 4 hours of heat exposure, during which they walked on a level treadmill at 1.3 m/s for 25 minutes and sat for 5 minutes every half hour. They wore the Navy utility uniform, which has a thermal insulation of 1.1 clo and water vapor permeability (i_m) value of 0.6. When the cooling vest was used, it was worn over the shirt.

Parameters measured included rectal temperature, skin temperatures at three sites, heart rate, total body sweating rate and gel pack temperature. When the gel pack reached approximately 20°C, the packs were replaced. The packs were also checked

manually to ensure that they were replaced when almost melted. The time of each coolant change was recorded.

Results

In all environments, the SteeleVest significantly reduced thermal strain, as evidenced by reduced rectal and skin temperatures, heart rate and sweat rate. Changes in rectal temperature data from 36°C, 38°C, and 39°C WBGT environments are plotted in Figures 12, 13, and 14, respectively. In all environments, there were significant differences ($p<0.05$) in the rectal temperatures when the control and the SteeleVest tests were compared.

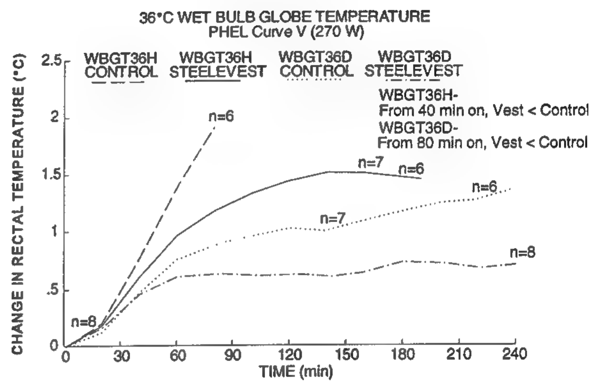

Figure 12. Change in rectal temperature with and without the SteeleVest.

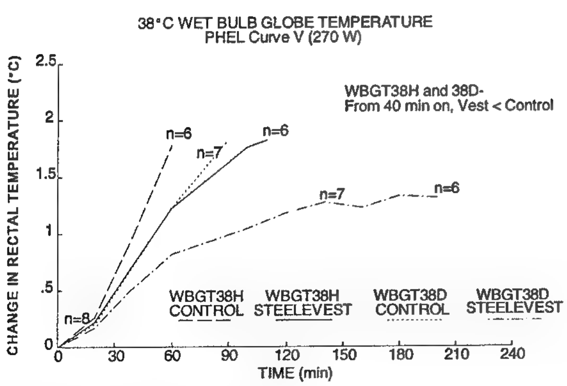

Figure 13. Change in rectal temperature with and without the SteeleVest.

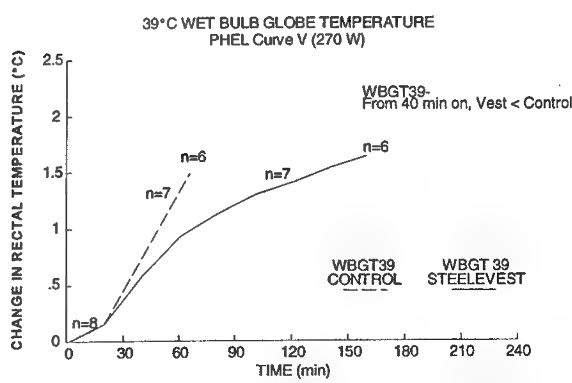

Figure 14. Change in rectal temperature with and without the SteeleVest.

Mean weighted skin temperatures in the 36°C, 38°C and 39°C WBGT environments are shown in Figures 15, 16, and 17, respectively.

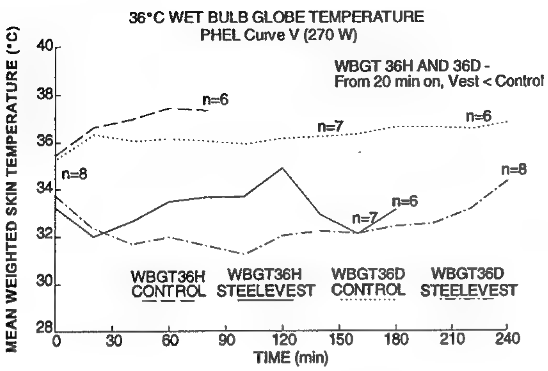

Figure 15. Mean weighted skin temperature with and without the SteeleVest.

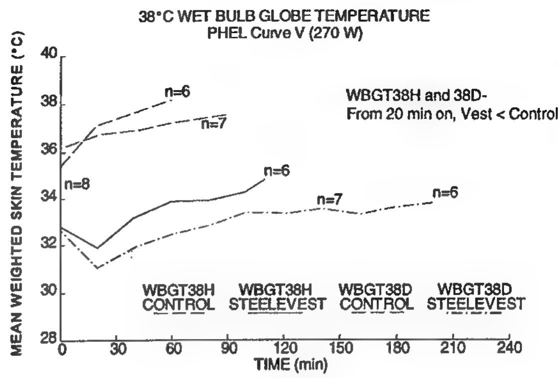

Figure 16. Mean weighted skin temperature with and without the SteeleVest.

There were significant differences ($p<0.05$) in the mean weighted skin temperatures in all environments when the control and the SteeleVest tests were compared. Heart rates during each of the heat exposures are presented in Figures 18-20. As with the rectal and mean weighted skin temperatures, the heart rate was significantly ($p<0.05$) lower when the SteeleVest was used than during the control tests in all environments. Figure 21 illustrates total body sweat rates with and without the SteeleVest in each of the five environments. In each environment, sweat rate was lower when the SteeleVest was used than during the control test ($p<0.05$).

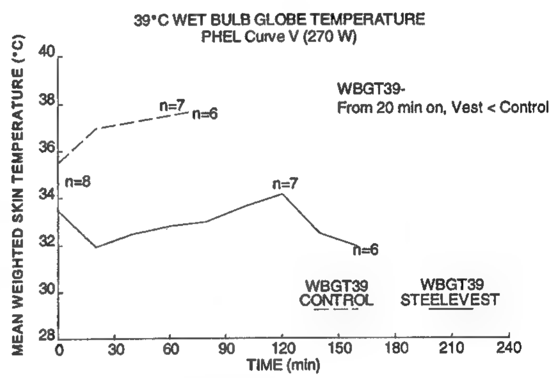

Figure 17. Mean weighted skin temperature with and without the SteeleVest.

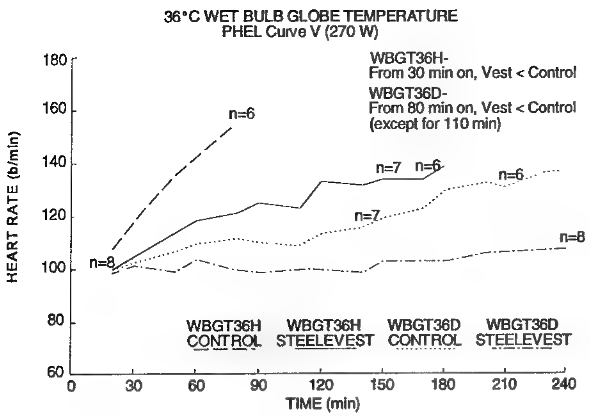

Figure 18. Heart rate over time with and without the SteeleVest.

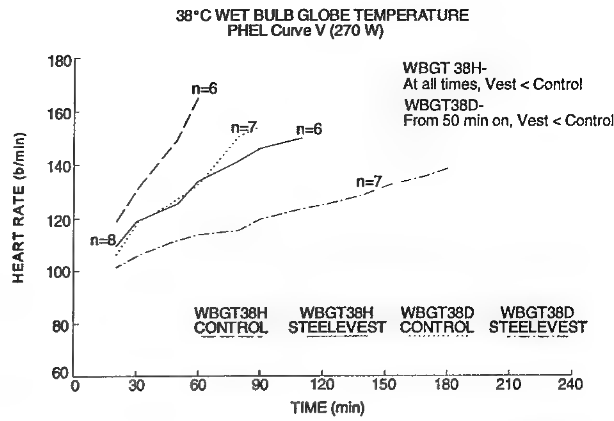

Figure 19. Heart rate over time with and without the SteeleVest.

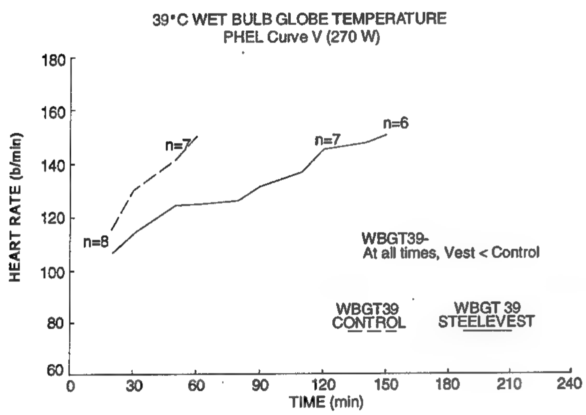

Figure 20. Heart rate over time with and without the SteeleVest.

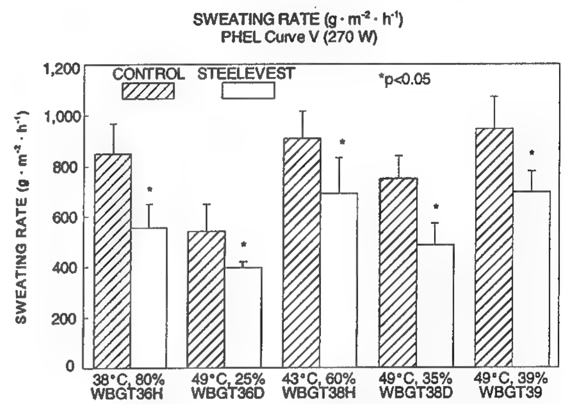

Figure 21. Total body sweating rate with and without the SteeleVest. T indicates SD.

Discussion/Conclusions

In all environments, the SteeleVest significantly reduced thermal strain, as evidenced by reduced rectal and skin temperatures, heart rate and sweat rate. Use of the SteeleVest approximately doubled tolerance times compared with tests without the vest. The gel packs lasted approximately 2 hours before they required replacement. When the hot-humid and hot-dry environments having equivalent WGBTs were compared, thermal strain was higher in the more humid environments.

In addition to its effectiveness in reducing heat strain, the SteeleVest is relatively lightweight, has a low profile, requires little maintenance and is not susceptible to mechanical problems. These characteristics make it very desirable for shipboard use.

Study #8 Ability of a Passive Microclimate Cooling Vest to Reduce Thermal Strain and Increase Tolerance Time to Work in the Heat.

Introduction

Based on its ability to reduce thermal strain as well as its ease of operation and low maintenance, a "passive" cooling system was recommended for U.S. Navy shipboard use. The selected system consists of an insulated, fire-retardant cotton canvas vest with six pockets (three on the front, three on the back) which each hold a frozen gel strip against the torso. The total weight of the system is 5.1 kg.

A previous NCTRF study (9) had evaluated the passive MCS at a metabolic rate of 272 W, which represents the fifth of six curves comprising the Navy's Physiological Heat Exposure Limit (PHEL) curves. This study (10) describes the physiological responses to the environment-work combination described by PHEL curve III (metabolic rate = 208 W).

Test Method

Fourteen male volunteers (average age, 21 yr; height, 179 cm; weight, 80.2 kg) underwent 8 days of heat acclimation followed by six heat stress tests. The heat stress tests were conducted in three different environments: environment A = 44°C dry bulb

(db) temperature, 46°C black globe (bg) temperature and 49% relative humidity (rh); environment B = 51°C db, 53°C bg and 33% rh; environment C = 57°C db, 59°C bg and 25% rh. In each environment, each volunteer performed two heat stress tests: once while using the cooling vest and once without (control test). During each test, volunteers attempted to complete a 6-hour exposure while alternating 20 minutes of treadmill exercise (at a speed of 1.1 m/s on a 3% grade) with 40 minutes of seated rest. This resulted in a time-weighted metabolic rate of 208 watts. Subjects wore the U.S. Navy utility work uniform (thermal insulation = 1.1 clo; water vapor permeability (i_m) index = 0.6). When the cooling vest was used, it was worn over the T-shirt and work shirt. Physiological measurements included rectal temperature; chest, upper arm, calf and thigh skin temperatures; heart rate; and total body sweating rate. Because of voluntary attrition during the control tests, statistical comparisons were made up to the following times: 200 minutes in environment A, 80 minutes in environment B, and 60 minutes in environment C.

Results

In environment A, five of the 14 volunteers were able to complete the 6-hour heat exposure during the control test. When the cooling vest was used, all 14 volunteers completed the exposure. In environments B and C, use of the cooling vest more than doubled tolerance time compared with the control tests. The increase in tolerance time due to the vest averaged approximately 3 hours in environment B, and over 1.5 hours in environment C. In all three environments, use of the vest resulted in

significant reductions in rectal temperature, chest temperature, heart rate and sweating rate compared with the control tests ($p<0.05$). Upper arm, calf and thigh skin temperatures were not significantly different between the cooling vest and the control tests ($p>0.05$). The reduction in rectal temperature when the vest was used averaged 0.4°C in environment A (after 200 minutes of heat exposure), 0.7°C in B (after 80 minutes of heat exposure), and 0.8°C in C (after 60 minutes of heat exposure). The reduction in chest temperature averaged 8°C in environment A (at 200 minutes), 8°C in environment B (at 80 minutes) and 5°C in environment C (at 60 minutes). Heart rate was reduced by 18, 25 and 20 b/min in environments A (at 200 minutes), B (at 80 minutes) and C (at 60 minutes), respectively. Use of the cooling vest reduced total body sweating rate by 49%, 45% and 38% in environments A, B and C, respectively.

Discussion/Conclusions

Use of the passive cooling vest significantly reduced thermal strain, as evidenced by reduced rectal temperature, chest temperature, heart rate and sweating rate. When the cooling vest was used by volunteers wearing a standard work uniform and performing light exercise in extreme hot environments, work time was more than doubled compared with control tests. Use of the vest reduced total body sweating rate by an average of over 40%. Drinking water requirements, therefore, would also be lowered.

The significant increases in tolerance times demonstrated in references (9) and (10), clearly show the advantages of MCS use in the Navy. With the doubling of stay

times, fewer personnel would be required to man the hot engine spaces; and therefore, more personnel would be available for other duties. Also, because the sailors would sweat less and core temperatures would rise less during their watches, they would presumably be in better physical and mental status at the end of their duty periods.

Study #9 Heat Stress Induced By the Navy Fire Fighter's Ensemble Worn in Various Configurations.

Introduction

The Navy Fire Fighter's Ensemble (NFFE) including the non-aluminized damage control coverall was introduced to the Fleet in 1988. During the following year and a half, some instances of heat stress problems related to use of the NFFE were reported. Problems with heat stress occurred primarily during main space fire drills when personnel were fully dressed out in the NFFE and, in some cases, when also using an Oxygen Breathing Apparatus. When the heat injuries occurred, the average length of time the NFFE had been worn was 36 minutes. The injuries occurred mostly during training drills when personnel completely dressed out in the NFFE were engaged in very low levels of physical activity.

In response to these reports of problems with heat stress when the NFFE was worn, NCTRF conducted a laboratory evaluation of the NFFE (11). The primary purpose of the evaluation was to measure heat strain when the NFFE is worn in a "buttoned up" configuration and to determine to what extent wearing the NFFE in a more relaxed or standby configuration alleviates this heat strain. The secondary

purpose of the study was to examine the effectiveness of a selected cooling vest in reducing heat strain used with the NFFE.

Test Method

NCTRF conducted a laboratory evaluation to compare heat stress when the NFFE is worn, with and without a cooling vest, in three configurations: 1) coverall "buttoned up" with anti-flash hood, helmet and gloves worn, 2) coverall unzipped with hood around neck and no helmet or gloves worn, and 3) coverall down around the waist with hood around neck and no helmet or gloves worn. The cooling system was a cotton canvas vest which holds 4.5 kg of frozen gel packs (Steele, Inc.). Nine test volunteers underwent six, 2-hour heat exposures (three NFFE configurations with and without the cooling vest). Environmental conditions were 32°C dry bulb temperature with 60% relative humidity. During the heat exposures, the test volunteers alternated seated rest with walking 1.56 m/s on a treadmill every 15 minutes. These conditions were chosen to simulate a drill during which the level of physical exercise is low.

Results

When the NFFE was worn buttoned up, and when it was worn in the unzipped configuration, use of the Steele cooling vest significantly reduced thermal strain. When the cooling vest was worn, the increase in core temperature after 2 hours of heat exposure was only half that of the uncooled conditions. Mean weighted skin temperature was significantly reduced, and heart rate was reduced by 21-36 b/min.

Total body sweating rate was reduced by approximately 40%. When the coverall was worn around the waist, however, and overall thermal strain was only moderate, the vest further reduced heat stress only slightly. In that condition, the logistics involved in freezing and storing the gel packs probably do not warrant use of the cooling system.

Discussion/Conclusions

The study demonstrated that, if the U.S. Navy Fire Fighter's Ensemble (NFFE) is worn with the coverall down around the waist, heat stress is greatly reduced compared with wearing the coverall just unzipped, or with wearing the ensemble completely buttoned up. While personnel may need to practice donning and wearing the complete ensemble, in warm weather it should be worn in this configuration for very limited time periods only. If the coverall cannot be worn down around the waist, thermal strain can be significantly reduced by using the Steele cooling vest. While the vest may be effectively used to reduce heat strain during training drills, use of the vest may be an unsafe practice in an actual fire fighting situation. Because of the potential for a burn injury, exposure times for fire fighting personnel may be limited to very short periods during high intensity fires. In this case, use of an auxiliary cooling device such as an ice vest may reduce overall thermal strain but does not decrease the potential for a burn injury. Because of this, the added comfort provided by the cooling vest may result in a false sense of well-being if worn during actual fire fighting. Further evaluation of MCS needs to be done during actual firefighting scenarios to determine its applicability to high intensity heat.

THERMAL MANIKIN STUDIES

Study #10 Passive Cooling for Encapsulating Garments

Introduction

Personnel wearing encapsulating clothing will more readily suffer heat stress under certain conditions due to the added insulation and reduced vapor permeability of such ensembles. Passive cooling vests (e.g. the SteeleVest) are useful for reducing heat stress when worn with general utility clothing (6,9,10) and have found widespread use in both the military and industry. These vests are not practical for use with encapsulating ensembles; however, since wearing the vest over the ensemble reduces the cooling effect, and wearing the vest under the ensemble prevents changing of the cooling packs. Increasing the number of cooling packs and incorporating the pockets for the packs directly into the ensemble may be a relatively easy way to provide cooling in encapsulating clothing. The purpose of this study was to test this concept on a Thermal Manikin (TM) (12).

Test Method

TM testing was conducted on a prototype U.S. Navy Chemical Protective Overgarment (CPO) and the Toxicological Agent Protective (TAP) suit. The CPO is a semi-permeable ensemble whereas the TAP is impermeable. Both ensembles were tested with three cooling variations: a passive MCS (the SteeleVest) under the ensemble (U), over the ensemble (O), and the ensemble modified by adding exterior pockets for the cooling packs to the torso and thigh surfaces (M). The M-CPO and

M-TAP contained 29 cooling packs (7.4 kg of gel) compared to 18 (4.6 kg) in the SteeleVest. The gel packs were frozen at approximately -15°C prior to the test. Tests were run at 35°C, 60% relative humidity, 0.9 m/s wind speed, and 35°C TM temperature. TM power was measured without cooling packs (baseline) and at 1-min intervals after the cooling packs were inserted. Cooling results were determined by the average of 120 consecutive power readings less the baseline.

Results

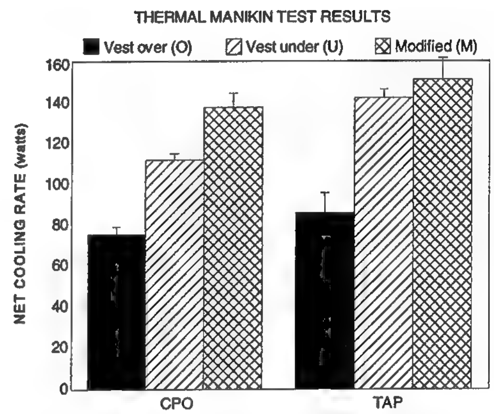

Figure 22. Thermal manikin test results.

The test results are illustrated in Figure 22. The cooling provided by M-CPO (137 W) was significantly greater than U-CPO (112 W) and O-CPO (75 W). The cooling provided by M-TAP (151 W) was equivalent to U-TAP (142 W) and significantly greater than O-TAP (86 W).

Discussion/Conclusions

These results demonstrate that external passive cooling packs may be a viable solution to heat stress problems in both semi-permeable and impermeable encapsulating clothing ensembles. If 29 external packs (7.4 kg gel) are used, the cooling provided is at least equal to the use of the SteeleVest under the ensemble.

Study #11 Effectiveness of a Prototype Microclimate Cooling System for Use with Chemical Protective Clothing - (Thermal Manikin Evaluation)

Introduction

The purpose of this thermal manikin (TM) evaluation was to assess the theoretical and actual cooling capabilities of a prototype MCS for use with chemical protective overgarments. This prototype MCS was also evaluated in a human laboratory test as described in study #6 of this report and in reference (7). Brief descriptions of the chemical protective overgarments (the Mark III (MKIII) and the Mark III with the Navy Wet Weather ensemble (MKIII+WW)) and the prototype MCS may be found in study #6 of this report.

Five parameters were evaluated. The theoretical cooling capacity identifies the maximum cooling potential of the MCS. Actual cooling capacity describes the amount of cooling provided to (i.e., the amount of heat actually removed from) the user. The efficiency of the system provides a representation of how close the actual capacity comes to its theoretical capacity. The last two parameters, ice reserve life and average cooling rate, indicate how long the system will last, and how quickly it removes heat. These parameters are valuable since they indicate in a practical way the cooling that a user of the system should expect.

Test Method

The conditions during the tests were 35°C ambient temperature, 60% relative humidity, 0.9 m/s wind speed, with the manikin surface temperature maintained at 35°C

and a fully wetted sweating skin. The MCS vest was worn under the chemical defense garment.

Each test was conducted in two phases, a control (no cooling) phase followed by a cooling phase. During the control phase, the TM was allowed to reach thermal equilibrium with the cooling system turned off, and no ice reserve in the backpack. Once thermal equilibrium was reached, the amount of power required by the TM to maintain surface temperature was noted. At this point, an ice reserve was placed into the backpack, and the cooling system was turned on. This began the cooling phase of the test. The power required by the TM was recorded at one minute intervals during the cooling phase. The difference between the power consumed during the control phase and power consumed during the cooling phase indicates the cooling power of the MCS. The temperature of the fluid entering the vest was monitored until it reached 18°C, at which point the test was ended.

A computerized data acquisition system was used to collect circulating fluid temperature data from the MCS. Thermocouples were placed in the circulating lines of the MCS at four points: entering and exiting the ice pack, and entering and exiting the vest itself.

The required calculations included theoretical cooling capacity, actual cooling capacity, efficiency, and average cooling rate. The theoretical cooling capacity of the MCS is based on the amount of ice or water in the ice reserve and the allowable temperature rise. There are two equations which govern the theoretical cooling capacity of the MCS. The first equation describes the cooling associated with heat

absorption by the ice (before melting) as it rises from its initial frozen temperature to 0°C. The first equation also describes the cooling associated with the heat absorption by the water (after the ice has melted) as it rises from 0°C to its final temperature.

$$Q = MC(Tf-Ti) \qquad (1)$$

Where:

- Q = heat absorbed
- M = mass of ice or water in the ice pack
- C = heat capacity of ice or water
- Tf = final temperature
- Ti = initial temperature.

Any consistent set of units may be used in this equation.

The second equation describes the heat absorption of the ice as it melts at 0°C.

$$Q = MH \qquad (2)$$

Where:

- H = latent heat of fusion of ice and other variables are defined above.

The theoretical cooling capacity was calculated by using the first equation to calculate the heat absorbed by the ice as it rose to its melting point (0°C) followed by use of the second equation to calculate the heat absorbed by the ice as it melted. Next, the first equation was used again to calculate the heat absorbed by the water as its temperature rose above 0°C. Finally, the three heat absorption values were summed to determine the theoretical cooling capacity of the MCS.

Before the theoretical cooling capacity could be calculated it was first necessary to establish initial (ice) and final water temperatures in the ice pack. The ice packs were frozen to approximately -15°C. However, by the time the ice packs were

transferred from the freezer to the backpack, the hoses connected, and the system started, the temperature of the ice in the backpack had risen to approximately -10°C. Therefore, it seemed reasonable to select -10°C as the starting temperature for the theoretical cooling power calculation. As described earlier, the TM tests were discontinued when the temperature of the fluid entering the vest reached 18°C, therefore this temperature was selected as the final temperature for the theoretical cooling capacity calculation. The time required to reach this end point was termed the ice reserve life of the MCS.

The actual cooling capacity was calculated from the power input to the TM. The power input was recorded every 60 seconds. The control (no cooling) was subtracted from each of the 60-second power input readings taken during the cooling phase. This yielded the rate of heat absorption by the vest from the TM for each 60-second interval. To convert the rate of heat absorbed during each 60-second interval to the quantity of heat absorbed during each interval, the rates were multiplied by time. These results were then summed for the full length of the test to derive the actual cooling capacity of the MCS. Efficiency was calculated by dividing the actual cooling capacity by the theoretical cooling capacity, and multiplying by 100 to obtain percent. Average cooling rate was calculated by dividing the actual cooling capacity by the ice reserve life of the system.

Results

The theoretical cooling capacity of the ice reserve was 538 watt-hours. Most of the cooling (78%) was provided by the heat of fusion of the ice as it melted.

The average actual cooling capacity of the MCS when worn under the MKIII was 326 watt-hours. When worn under the MKIII+WW, the average actual cooling capacity was 308 watt-hours. This represented MCS efficiencies of 61 and 58%, respectively.

The average ice reserve life of the MCS when worn under the MKIII was 163 minutes (2.7 hours). When the WW was added, the average ice reserve life was 123 minutes (2.0 hours). The average cooling rates of the MCS worn with the MKIII alone and worn with the MKIII+WW were 122 and 151 watts, respectively.

Discussion/Conclusions

The actual cooling capacities of 326 and 308 watt-hours translate into efficiencies of 61% and 58%, respectively. It is theorized that the actual cooling capacity and efficiency of the MCS can be increased by reducing heat absorption from the environment. During the TM tests, the temperature of the circulating fluid rose by 5 to 10°C as it flowed from the ice reserve to the vest through uninsulated tubing that was exposed to the environment. Insulating these flow lines should result in a significant improvement to the actual cooling capacity and efficiency of the system. Adding insulation to the backpack itself should also reduce heat gain from the environment.

Conclusion

The U.S. Navy Clothing & Textile Research Facility has been involved in the development and testing of MCS for Navy applications for many years. Commercial and prototype systems have demonstrated that MCS significantly reduce heat strain in hot environments. Commercial systems generally require some modification (such as covering the exterior of the MCS with a fire retardant material) before they can be used on board ship.

Studies have demonstrated that both portable ice-based liquid circulating and passive cooling systems have proven effective for use with general utility clothing for US Navy applications. The Model 1905 Cool Vest manufactured by ILC Dover, Inc. and the SteeleVest manufactured by Steele, Inc. demonstrated overall superior performance in terms of cooling effectiveness, logistics, cost, reliability and maintainability when compared to other commercial systems. However, because of logistics problems associated with battery storage and recharging, portable ice based liquid MCS has not been well received on board ship. Only the passive cooling system has been widely used and can be procured through the supply system with a commercial item description (13).

Passive MCS has been shown to significantly increase the stay times of individuals working in hot environments at metabolic rates described by Navy Physiological Heat Exposure Limit curves III (208 W) and V (272 W). For Navy applications, the increase in stay times over those described by the PHEL curves implies that fewer personnel should be required for some watch duties. Further,

because sweating is reduced with use of a MCS, the hydration status of the sailor completing the watch in a hot space should be better when a MCS is used.

The passive MCS are of limited use with encapsulating garments such as the Navy Chemical Protective Overgarment and Fire Fighter's Ensemble. Once the ice packs melt, cooling is no longer provided and an additional thermal burden may be incurred. Replenishment requires doffing the ensemble, which may not be practical in contaminated environments. However, NCTRF has demonstrated that under some fire fighting applications, such as training drills, MCS may be useful in reducing the thermal burden of individuals completely outfitted in a fire fighter's ensemble. NCTRF is currently developing and evaluating prototype MCS for impermeable applications. Preliminary laboratory work has shown the prototypes to be effective in significantly reducing heat strain.

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TECHNICAL REPORT

AL-TR-1993

USAF PHYSIOLOGICAL STUDIES OF PERSONAL MICROCLIMATE COOLING: A REVIEW

by

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Final Report for Period September 1980 - December 1992

ARMSTRONG LABORATORY
AIR FORCE MATERIEL COMMAND
BROOKS AIR FORCE BASE, TEXAS

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LIST OF ACRONYMS AND ABBREVIATIONS

T_{db}	dry bulb temperature
T_{wb}	wet bulb temperature
T_{bg}	black globe temperature
T_{re}	rectal temperature
T_{sk}	skin temperature
$\bar{T}_{sk}$	mean skin temperature
WBGT	wet bulb globe temperature
CW	chemical warfare
CD	chemical defense
CDE	chemical defense ensemble
GCLCS	ground crew liquid cooling system
MOPP IV	Mission Oriented Protective Posture (Maximum Level)
MICS	Multiman Intermittent Cooling System

NOTE: All human subjects were fully informed of the purposes and possible risks of the individual study and signed voluntary consent statements in accordance with Air Force Reg. 169-3.

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EXECUTIVE SUMMARY

The U.S. Air Force has accomplished a number of research studies which evaluated the efficacy of selected personal cooling approaches for the alleviation of heat stress when wearing certain protective clothing. Most of this work involved laboratory as opposed to field studies and incorporated human subjects performing work in either warm or hot environments. Both air and liquid microclimate cooling systems were employed. The general findings are several fold: 1) personal microclimate cooling systems (both air & liquid) were shown to remove significant quantities of body heat, 2) in general, commercially available systems were inferior to in-house prototype units, 3) backpack (ambulatory) systems usage would likely have a limited user audience for a number of reasons, 4) some new-term, partial solutions to the problem may be at hand for selected deployments and, 5) microclimate cooling technologies on the horizon will likely not provide an optional solution for most ground crew applications. The USAF Armstrong Laboratory has no plans for further research in this area.

INTRODUCTION

Performance of many U.S. Air Force (USAF) mission-critical tasks requires personnel to sustain moderate-to-hard levels of work for extended periods. Performance of military operations within a chemical warfare (CW) threat environment imposes additional stressors that include both physiological and psychological factors related to the actual or potential exposure to chemical agents. For example, currently-available individual chemical protective equipment--the Chemical Defense Ensemble (CDE)--imposes specific burdens which can ultimately influence performance. Physical constraints of the CDE include reduced visibility, impaired communication, and diminished manual dexterity and mobility; these combined functional decrements can significantly affect task performance.

With respect to sustained work, however, the most important burden imposed by the CDE is the marked impediment of physiological thermoregulatory processes. The CDE consists of a heavyweight garment with low permeability, and impermeable mask, hood, boots and gloves: it retards evaporation and significantly impedes heat transfer from the body. This constraint on heat dissipation is paramount in certain warm or hot climatic environments, while the effects of this constraint are greatly exacerbated as the work rate increases. In addition to the effect on task degradation and early exhaustion, wearing CDE while working at an increased metabolic rate can provoke heat stroke or death without medical or other intervention.

When all of these factors are considered together, it is easy to forecast a potentially disastrous situation for some troops wearing the CDE during sortie

generation in airfield operations. It is this concern that has prompted the USAF and other branches of the armed forces, to seek solutions to this thermal predicament. Notwithstanding workload, the environmental climatic status is probably the major factor in determining the severity of the problem; however, this condition is virtually uncontrollable. Prophylactic approaches that have been forwarded include: frequent rest periods; reduced workload; thermal acclimation; increased aerobic conditioning; a less thermally-burdening CDE; mass cooling areas; and personal cooling devices.

In the past, it has been the consensus that the last option--i.e., personal cooling systems incorporated into the CDE--may hold the greatest potential for real success in solving most of this problem. However, some researchers have begun to question the potential for full achievement of the goals using this strategy. This report will review the cooling problem with regard to past USAF work.

PHYSIOLOGICAL BACKGROUND

Humans, like many machines which perform work, oxidize fuel to obtain energy. However, biological machines do not convert the heat of oxidation into work; rather the body oxidizes food substrates at a relatively low temperature, and converts this chemical energy into work and heat. Biological cells need this energy for certain "housekeeping" work such as the active transport of certain solutes across membranes. In concert with the first law of thermodynamics, all of this "internal work" eventually shows up as heat. Larger amounts of energy are needed when the body becomes physically active and performs "external work". Very large quantities of heat may then

be produced. Even at rest, the body heat production is significant and important to the maintenance of physiological homeostasis.

Metabolic heat is normally dissipated to the environment by several means. The primary mechanism involves the conduction of thermal energy from the tissues to the circulating blood, where the heat is transported (convected) to the body surface; it is then eliminated by conduction, convection, evaporation, or radiation. Most important is the maintenance of an isothermal body core temperature throughout a range of environmental conditions. However, the heat-transfer processes are largely influenced by external environmental conditions. In warm or hot climates, heat removal from the body may be especially limited and will be further affected by a change in metabolic rate. Remarkably, heat production may be accelerated from rest by a factor of 10 to 15 during extremely heavy work. Therefore, both the external (environmental) and internal (metabolic) heat load affects the body's ability to thermoregulate. When the heat load is heavy, the entire cardiovascular system is taxed and work performance becomes compromised. Wearing the CDE under these circumstances may easily overburden the body's thermoregulatory system and ultimately lead to heat illness or heat stroke unless preventive or mechanical intervention is practiced.

PHYSIOLOGICAL RESEARCH OVERVIEW

Wearing individual protective equipment (IPE) such as the chemical defense battle dress overgarment (BDO) can be debilitating from a thermal balance standpoint. Auxiliary personal cooling has been suggested to provide relief or significant

attenuation from this heat stress. The armed forces have evaluated various microclimate cooling approaches which might be implemented in the field. USAF first investigated both in-house and commercial "backpack" (ambulatory) systems. The heat sinks here were either an ice slush or refrigerant. Both approaches were configured in a recirculating closed loop configuration. In collaboration with the U.S. Army, an open-loop freon based system was additionally tested. The physiological payoff from these systems was always relatively low; often the estimated "logistical tail" in the field would have been prohibitive. A novel concept of marrying the required rest cycles with personal cooling (intermittent cooling) was later investigated. Both chilled liquid and air intermittent cooling approaches appeared promising in the laboratory. This concept, later termed multiman intermittent microclimate cooling system (MICS), incorporated chilled air in an open-loop configuration. Finally, a simplified, lightweight, ambient air cooling approach was tested for its human efficacy in the environmental chambers. Again, this concept appeared promising as a partial near-term answer to this difficult problem. Finally a summary of each USAF human physiological study is included in this comprehensive report.

BACKPACK COOLING STUDIES

Study #1 (Chamber Trials of LSSI Unit)

This study evaluated a commercially produced liquid cooling system suggested for ground crew application which consisted of a liquid cooling vest and cap; it was manufactured by Life Support Systems, Inc. (LSSI). Prefrozen ice cartridges functioned

as the heat-sink. In all experiments, the subjects (N=5) wore fatigues, the chemical defense ensemble (MOPP IV configuration) plus a flak jacket. For all liquid cooling trials, the cooling vest and cap were worn next to the skin; the LSSI support system (ice cartridges, power pak, etc.) was donned last. Two chamber environments were employed 32/21/38°C (warm) or 38/24/44°C (hot) T_{db}, T_{wb}, T_{bg}, respectively. The work consisted of treadmill walking for 12 min followed by a 3-min rest period, the sequence was repeated until the termination of the experiment which was usually because core temp = 39°C. The time weighted metabolic rates were approximately 400 kcal/ hr. Subjects attempted a maximum trial of two hours unless limited by high body core temperature or heart rate (≥ 85% HR max). There were four experimental conditions: i.e., a) warm/control vs. warm/cooling vest and b) hot/control vs. hot/cooling vest. In all figures, the lines represent the mean values for all subjects exposed to a condition; the line terminates as the first subject is withdrawn. The points indicated by letters represent the final value for each subject and show the interindividual variation in physiologic responses.

The use of the LSSI vest improved tolerance times an average of 36 and 43 minutes for the warm and hot environments, respectively. However, the cooling vest did not eliminate the thermal burden of wearing the CDE. The rate of heat conductance by the vest was quite variable during these experiments (Table 1). The range was 59 to 160 kcal/hr which represented 15% to 40% of the metabolic heat load.

These data provide only modest support to the concept of liquid cooling as an effective means of removing heat from working ground crew members wearing CDE.

The adequacy of the system evaluated for field use will be determined based on operational requirements. Improvements in this or similar systems will be needed to eliminate the thermal burden of and to allow prolonged work in the CDE because many logistical support concerns remain.

TABLE 1

Summary of Physiological Responses.

Condition	Exposure Time (min)	Rate of Rise in T_{re} (°C/hr)	Metabolic Rate (kcal/hr)	Vest Heat Removal Rate (kcal/hr)	Sweat Loss (%wt/hr)
Warm Control	62 ±3	1.7 ±0.2	409 ±29	no vest	4.36 ±1.8
Warm w/Vest	98 ±26	1.0 ±0.4	418 ±15	100 ±23	2.76 ±0.6
Hot Control	56 ±10	1.9 ±0.1	397 ±15	no vest	4.20 ±0.83
Hot w/Vest	93 ±24	1.0 ±0.2	403 ±7	105 ±21	3.78 ±0.36

Values are means ± S.E.

The heat removed by the vest somewhat retarded the rate of heat storage. Rectal temperature (T_{re}) rose more slowly during experiments with the vest compared to the control condition (Figure 1a). However, equilibrium core temperature was never

achieved; the final T_{re} normally exceeded the goal equilibrium T_{re} of 38.5 °C. Heart rate responded similarly; i.e., each exercise period elicited a higher HR than the one before, and each rest period showed less HR recovery than the previous rest period (Figure 1a). Mean weighted skin temperature (mean T_{sk}) was lowered with the vest (Figure 1b). However, the mean T_{sk} was usually substantially higher than Fanger's comfort range for this workload. The cooled T_{sk} was always warmer than the 26°C goal which was established by agreement prior to testing.

In summary, with the use of this commercial cooling system, under "warm" and "hot" conditions, tolerance time was increased an average of 40 minutes (range = 10 to 54 minutes). However, the thermal burden of wearing the CDE overgarment was not eliminated. Body core temperature (T_{re}) and HR continued

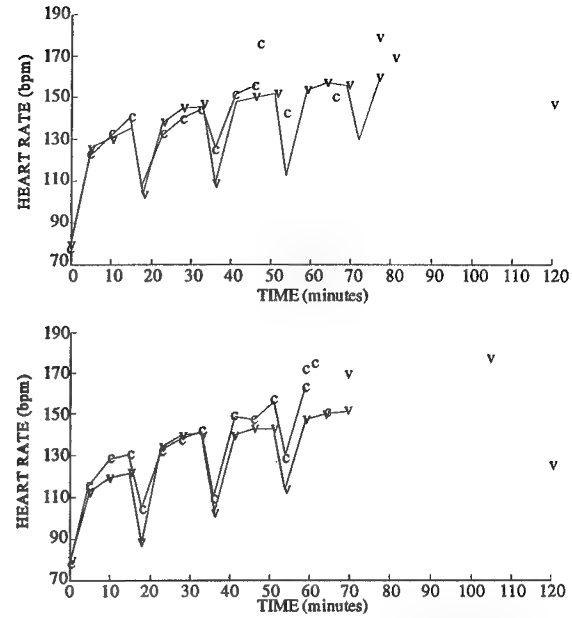

Figure 1a. Means and final HR in hot (top) and warm (bottom) environments. C = Control Tests; V = Cooling Vest Tests.

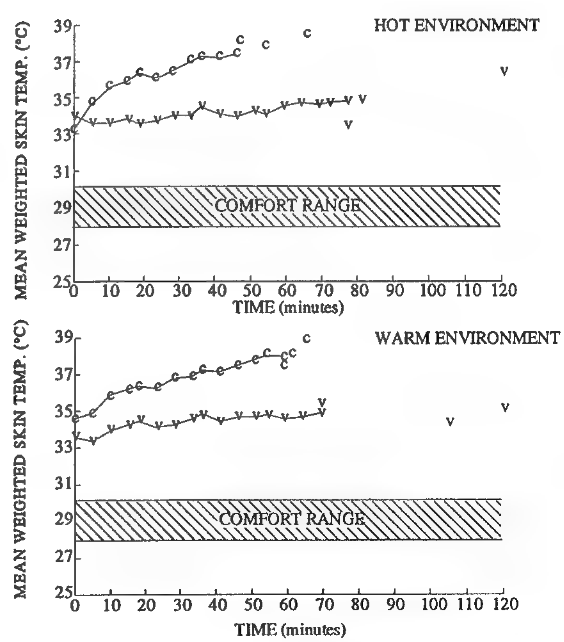

Figure 1b. Means and final mean skin temperatures. C = Control Tests; V = Cooling Vest Tests.

to climb during each experiment without indication of thermal equilibrium. The skin temperature under the cooling vest was too warm to inhibit heat storage effectively. Sweat loss remained in excess of 1.5% of body weight per hour.

Study #2 (ILC and LSSI Chamber Trial Comparisons)

In these experiments, two commercially available backpack, i.e. body mounted, liquid cooling systems were tested on both a completely wet (maximal sweating) copper manikin and with human subjects (N=9) wearing the CDE (MOPP IV). The systems which were tested are manufactured by ILC Dover (ILC) and Life Support Systems Incorporated (LSSI). Both systems, using ice as the heat sink, cool the torso by establishing a thermal gradient between the body surface and cool liquid circulating in the garment. The LSSI system also incorporated a liquid-cooled cap. The manikin was dressed in a cooling garment and the complete CDE and placed in a standing position in a large temperature- and humidity-controlled chamber; conditions were (T_{db}/T_{wb}): (a) hot (45/31°C) or (b) warm (32/22°C). The heat loss from the copper manikin was determined by measuring the power (Watts) required to maintain a constant manikin surface temperature. In this study, electricity was supplied to the torso to maintain an average temperature of 35°C; the head section was also heated to 35°C in tests on the LSSI system, since it included a cooling cap as well. The "cooling period" started at time zero when the ice packs were inserted into the heat exchanger and the pump motor was switched on.

The heat exchange provided by both the ILC and LSSI systems is plotted against time in Figure 2a. Heat loss from the manikin's surface was essentially the same at wet-bulb globe temperature (WBGT) indexes of 24.7 and 35.9°C, indicating that the heat sinks were well insulated from the outside environment. The cooling supplied by the ILC and LSSI units over the initial 2h averaged 74 W and 75 W respectively in the 24.7°C WBGT environment, and 66 W and 68 W in the 35.9°C WBGT environment. Not surprisingly, cooling provided by both systems diminished over time. Cooling has been shown to increase with agitation of the ice cartridge (Figure 2b). Thus, the amount of heat transfer measured on the passive copper manikin would be less than that measured on a human subject in motion.

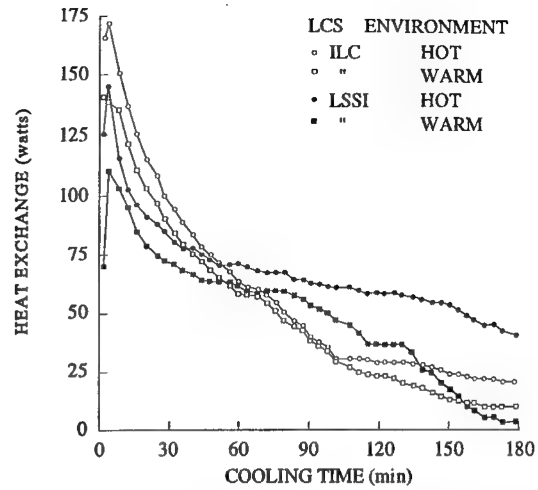

Figure 2a. Heat exchange provided by the ILC and LSSI liquid cooling systems on a wetted manikin.

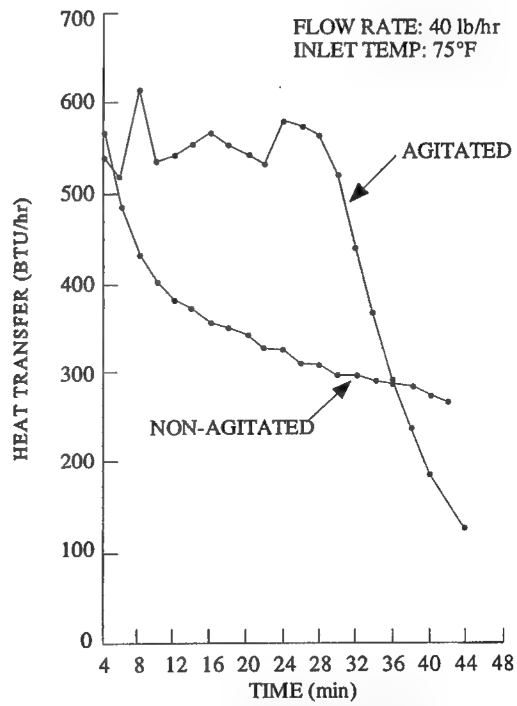

Figure 2b. Effects of physical agitation of ice cartridge (LSSI) on heat transfer.

Human subjects walked on a treadmill at 3.3 mph, 5% grade. Environmental conditions ($T_{db}/T_{wb}/T_{bg}$) were: hot = 45/31/50°C and warm = 32/22/37°C, respectively. The exercise consisted of alternating work (10 min) and rest (3 min) cycles with an estimated metabolic cost of 390-427 kcal/hr (time weighted). This regimen continued for 165 min, or until one or more of the following termination criteria was reached: (a) HR exceeded 180 bpm, (b) T_{re} exceeded 39.0°C, or (c) the subject was unable to continue. The rectal temperature, heart rate and mean skin temperature responses (hot conditions) are displayed in Figures 2c, d, and e, respectively.

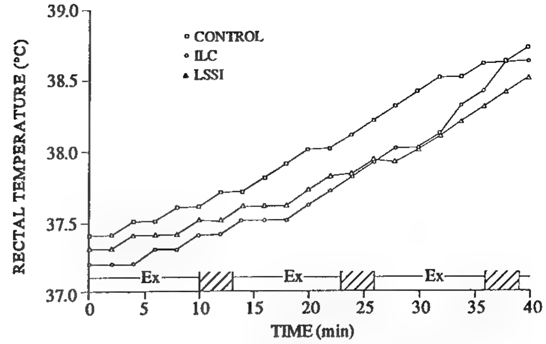

Figure 2c. Rectal temperature response under three experimental conditions in a hot environment.

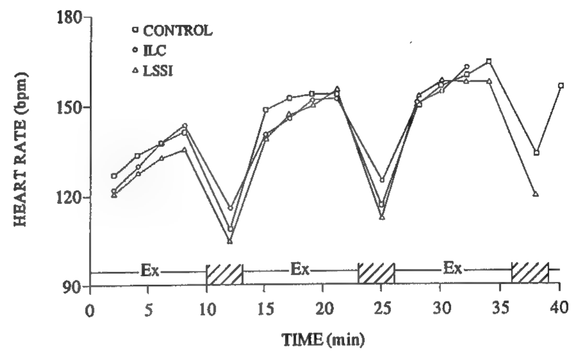

Figure 2d. Heart rate response under three experimental conditions in a hot environment.

Hot Conditions (WBGT = 35.9°C)

After the beginning of treadmill work, T_{re} rose at a rate of 2.4°C/hr, and this rise was not influenced by either cooling system: at 39 min of exposure

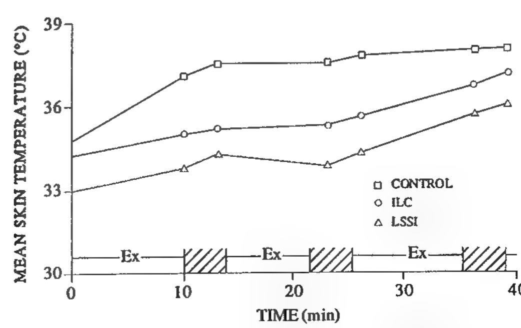

Figure 2e. Mean skin temperature response under three experimental conditions in a hot environment.

T_{re} ~ 38.5°C for all trials (Figure 2c). During the first three exercise bouts the mean HR rose by roughly 50 bpm (Fig. 2d). There were no differences in mean HR at the start of the experiment (124 bpm) or at the end of the third exercise bout (170 bpm). Sweat production and evaporation values are given in Table 2. No differences among conditions were observed in sweat rates or evaporation. Figure 2e gives the data for T_{sk} under each of the experimental conditions. Both cooling system decreased T_{sk} during the initial 30 min of exposure, but at 39 min these differences were insignificant. The cooling systems caused no change in the exposure time at which tolerance limits were reached. Therefore, neither of these personal cooling systems provided a significant thermal advantage over control under these conditions.

Warm Conditions (WBGT = 24.7°C)

There was some difficulty in comparing the two cooling systems because the ice had completely melted in both chillers by 75 min. The ILC system could not be recharged because, to do so, the overjacket and fatigue shirt had to be removed. Therefore, the ILC trial was ended after 75 min; however, the LSSI was easily recharged and the exposure time was extended to 165 min.

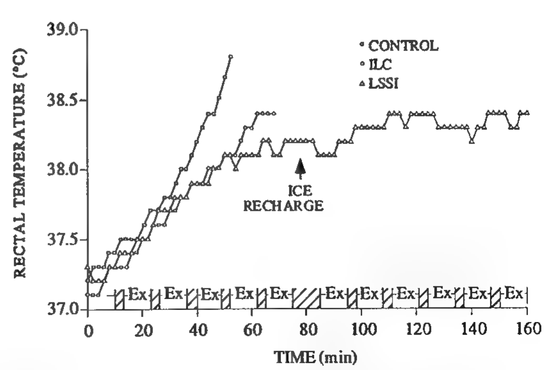

Figure 2f. Rectal temperature response under three experimental conditions in a warm environment.

Mean T_{re} values are given in Figure 2f. Rectal temperature rose at a rate of 1.7°C/h without an LCS and

reached a mean value of 38.8°C in 52 min. Both of the cooling systems significantly reduced the rate at which T_{re} increased: the ILC by 35% (1.1°C/h) and the LSSI by 47% (0.9°C/h). There were no significant differences between the ILC and LSSI units during the first hour of the experiment. Equilibrium levels of T_{re} ranged between 38.2°C and 38.4°C during the final 1.5 h of exposure with the LSSI unit. The mean heart rate (118 bpm) at the beginning of the experiment did not differ between experimental groups (Fig. 2g). Without auxiliary cooling all of the subjects were removed at a mean exposure time of 52 min, primarily because HR exceeded 180 bpm. By the end of the fourth exercise period, the mean HR was 164 bpm without cooling and 150 bpm with either LCS. During the final 1.5 h of exposure with the LSSI system, the mean HR was 146-160 bpm, with full recovery to pre-exposure rates during many of the 3-min rest periods. Mean skin temperatures are shown in Figure 2h. The mean sweat rate was reduced to 41% and 55% of the control value (1.353 kg/h) by the ILC and LSSI cooling systems, respectively (Table 2).

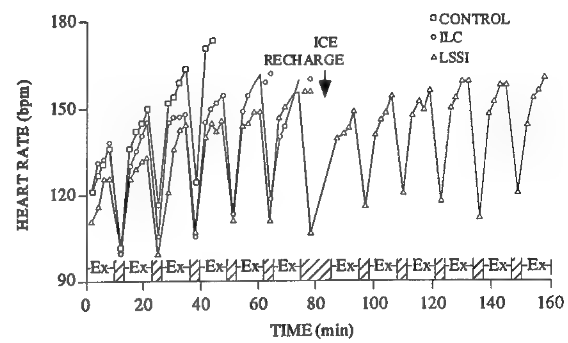

Figure 2g. Heart rate response under three experimental conditions in a warm environment.

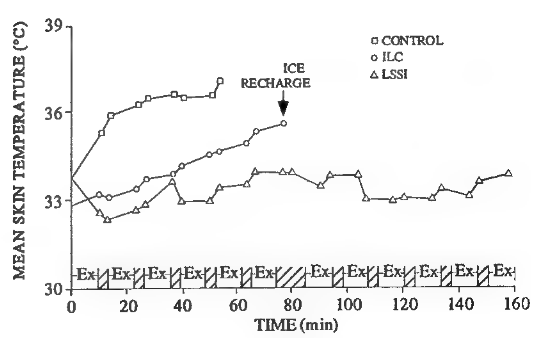

Figure 2h. Mean skin temperature response under three experimental conditions in a warm environment.

TABLE 2

Sweat and Evaporative Weight Loss. Mean (±S.E.)

Condition	Total Weight Loss (% body wt/hr)	Evaporative Weight Loss (% total)	Sweat Rate (kg/hr)
Hot Control	2.48 ± 0.53	34.5 ± 11.4	1.877 ± 0.368
ILC	1.81 ± 0.28	18.8 ± 4.9	1.425 ± 0.183
LSSI	1.89 ± 0.38	18.1 ± 4.7	1.509 ± 0.258
Warm Control	1.87 ± 0.24	19.9 ± 6.0	1.353 ± 0.262
ILC	0.78 ± 0.48	65.0 ± 25.0	0.559 ± 0.346
LSSI	1.05 ± 0.07	41.9 ± 2.2	0.742 ± 0.061

The mean tolerance time for the LSSI condition was 155 min. All of the subjects tested with the ILC chillers were removed after the sixth work bout, without reaching an experimental end point.

When the environmental heat load was less severe (24.7°C WBGT), both systems significantly reduced physiological strain. The LSSI system was more effective in this respect; both T_{re} and HR reached reasonable plateau values, which for T_{re}, T_{sk}, and HR were 38.3°C, 33.0°C, and 146-160 bpm, respectively. Sweat rates were also significantly reduced.

These researchers noted two important points: (a) that available portable liquid cooling systems can greatly enhance the ability of subjects to tolerate working in moderate heat while wearing a highly insulative overgarment, and (b) that a severe

environmental heat load (WBGT > 35°C) negates the thermal advantage from these particular systems. However, neither of the systems as tested was found suitable for USAF field operating conditions.

Study #3 (USAF Prototype Liquid Cooling System)

In Study #3, the physiological responses to the use of a developmental liquid cooling system was evaluated. Again, the goal was to alleviate heat stress when wearing the standard chemical defense ensemble (MOPP IV) configuration.

The prototype human-mounted portion of the system consists of a liquid cooled garment (LCG) and a backpack. The backpack which supports the heat sink, pump, and battery, was worn on the back with the weight evenly distributed between the shoulders and hips. The LCG is constructed of Tygon tubing interwoven into an elasticized net jacket. The total tubing length is 96 meters, and the effective cooling surface in contact with the skin is 0.52 square meters. The LCG extended from the hips across the shoulders and above the elbows so that the full torso, the shoulders and the upper arms receive active cooling. In each experiment, the subjects followed a work/rest cycle of 15 minutes exercise followed by 3 minutes of rest until the experiment terminated. Each experiment continued until one of four termination criteria was reached: T_{re} reached 39°C; HR reached 85% of age-predicted maximal; the subject reported intolerable fatigue; or 3 hours had elapsed.

This developmental backpack cooling system was tested in environmental conditions of $T_{db}/T_{wb}/T_{bg}$ = 38/24/44°C. Most of the data presented in this report was

confined to workloads of 415 kcal/hr (time-weighted average). A few trials were evidently conducted at other temperatures and work rates, but were not fully reported. The subjects exercised at a time-weighted metabolic rate of 415 kcal/hr in the 38/24/44°C environment.

Figures 3a and 3b present the responses of rectal temperature (T_{re}) and mean skin temperature (T_{sk}) in 5 subjects. A visual comparison with a commercial cooling system developed by Life Support Systems, Inc. (LSSI) is provided. These subjects had a mean tolerance time of 56 ± 10 minutes without cooling. During control experiments both T_{re} and T_{sk} rose continuously until the tolerance limit was reached and the subjects were removed from the thermal chamber. When subjects wore the LCG, all experiments continued for the full 3-hour time limit. Subjects reached an equilibrium T_{re} of 38 ± 0.1°C which was sustained throughout the experiment.

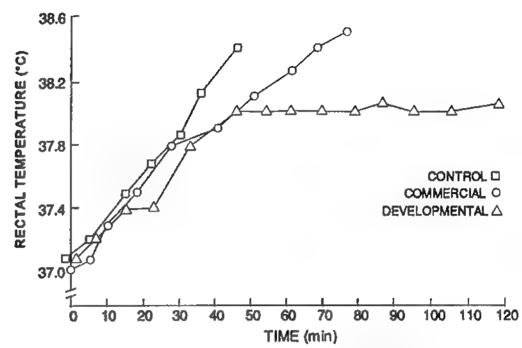

Figure 3a. Rectal temperature response under three experimental conditions in a warm environment.

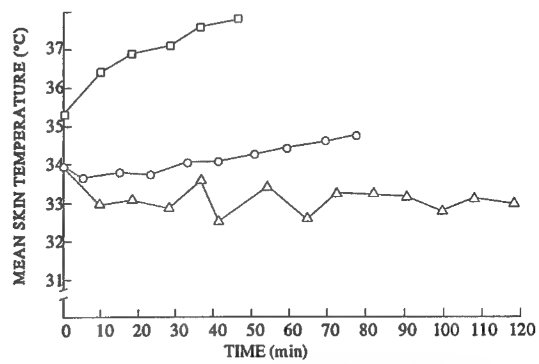

Figure 3b. Mean skin temperature response under three experimental conditions in a hot environment.

The effect of liquid cooling on sweating response is presented in Figure 3c. When subjects wore the system, but without auxiliary cooling total sweat production was 1.37 ± 0.41 L/hr. The fractional portion of this sweat production which was evaporated was 0.33, representing an efficiency of sweat output of 33%. Personal cooling reduced total sweat production to 0.69 ± 0.19 L/hr, while the efficiency of sweating was 55%. The total heat dissipation measured during these experiments is presented in Figure 3d. During control experiments, the only source of heat dissipation was evaporation of sweat. Sweat evaporation afforded 273 ± 40 kcal/hr of heat removal. The cooling vest and backpack restricted evaporation somewhat more than the CDE alone, resulting in heat removal by evaporation of 219 ± 30 kcal/hr. The auxiliary heat

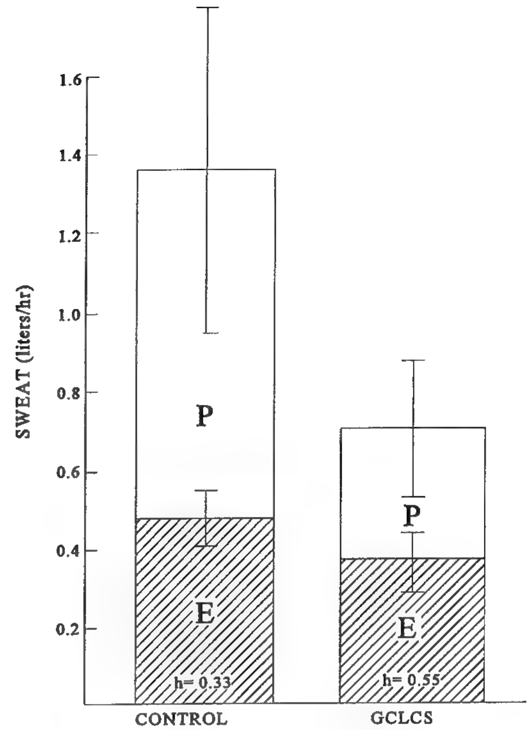

Figure 3c. Sweat production without (control*) and with (GCLCS) liquid cooling. * Cooling system still donned.

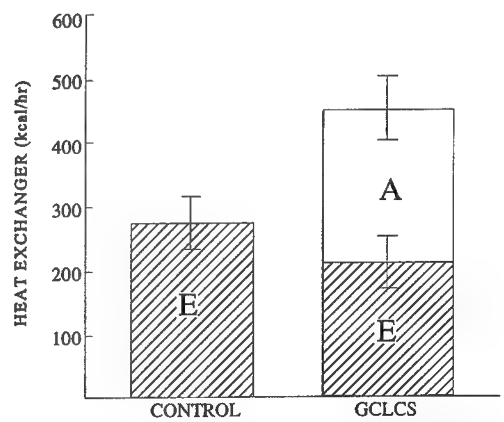

Figure 3d. Total heat loss without (control*) and with (GCLCS) liquid cooling. *Cooling system not donned.

removal via personal cooling was 240 ± 47 kcal/hr resulting in a total heat removal rate of 459 ± 36 kcal/hr.

Figure 3e presents a continuum of heat tolerance envelopes; it summarizes the envelopes of environments and workloads which can be tolerated by ground crew working in the near-term CDE. The clear area represents the tolerance envelope for the CDE with no auxiliary cooling. When environmental conditions are such that heat is neither gained nor lost via radiation and convection (see point a), approximately 219 kcal/hr of metabolic heat can be dissipated to the environment. As heat gain from the environment increases, the metabolic heat which can be tolerated decreases as is indicated by the downward trend of the tolerance envelope. The uppermost hatched area defines the tolerance envelope for the Ground Crew Liquid Cooling System (GCLCS) described herein. The metabolic heat production which can be tolerated is increased by the 240 kcal/hr which can be expected to be absorbed by the LCG. When heat is neither gained nor lost via radiation or convection, the total tolerable metabolic heat load is approximately 459 kcal/hr (see point b). For comparison, the tolerance envelope measured for the LSSI system is presented as well.

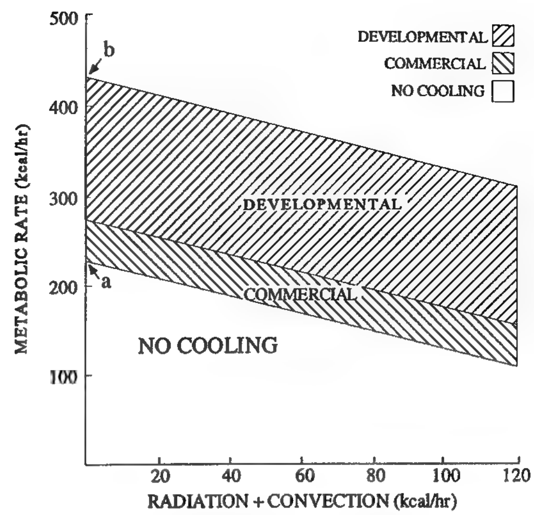

Figure 3e. Heat tolerance envelopes in subjects wearing the CDE (MOPP IV) performing work. The addition of a commercial and development cooling system is compared (see text).

The investigators concluded that the prototype personal cooling system did not dissipate enough heat to fully eliminate the thermal burden of wearing the CDE in all environmental extremes and under all workloads. However, many USAF ground crew tasks can be accomplished with the heat removal afforded by this system. Jobs with very high workloads, such as rapid runway repair, could be continued in hot weather for only limited time periods (approximately 2.5 to 3 hours).

Study #4 (Field Evaluation: Liquid Cooling & Training)

Study #4 evaluated the effects of proper training, careful pacing and adequate personal cooling on task performance. Thirteen male volunteer subjects performed rapid runway repair (RRR) exercises in a total of five experiments over as many days. These volunteers from an active duty squadron were mostly young enlisted members with an estimated aerobic capacity of 35.2 ml/min/kg. Each subject was tested while wearing: a) the full USAF ground crew CDE with all apertures closed (Closed), b) a portable water-cooling system under the closed ensemble (Closed w/Cooling), and c) standard fatigues with a protective hood and mask (Open). The ranking RRR team member was assigned the additional task of setting the work pace at as high a level as deemed possible under the prevailing circumstances and without incurring unnecessary "casualties". Training effects were assessed by testing all subjects in the Closed condition on experimental days 1 and 5. On the intervening days, each subject was tested in the Open and Closed w/Cooling conditions in a random order. Comparisons were made of physiological responses (rectal temperature - T_{re}; heart rate - HR; sweat

rate - SR) under the three experimental conditions to quantitatively assess the thermal strain contributed by the CD overgarments (Open vs Closed), and the extent to which auxiliary cooling alleviated this thermal burden under field conditions (Open vs Closed w/Cooling). The liquid cooling system employed here was not further characterized. Performance was assessed by documenting the rate of task completion and total amount of work performed, but was not reported. The mean environmental temperatures over the five exposure periods were as follows: 29.6_{db}, 24.8_{wb}, and 38.3_{bg}°C.

Figures 4a and 4b graphically summarize the key physiological data. Figure 4a shows that body heat storage (T_{re}) continued to rise at roughly 0.6°C/hr, and that five days of training significantly reduced the cardiovascular strain associated with performing RRR in a CD posture ($p < .001$), (Fig. 4b). The observed reduction in HR cannot be attributed to a difference in the environmental heat load on days 1 and 5.

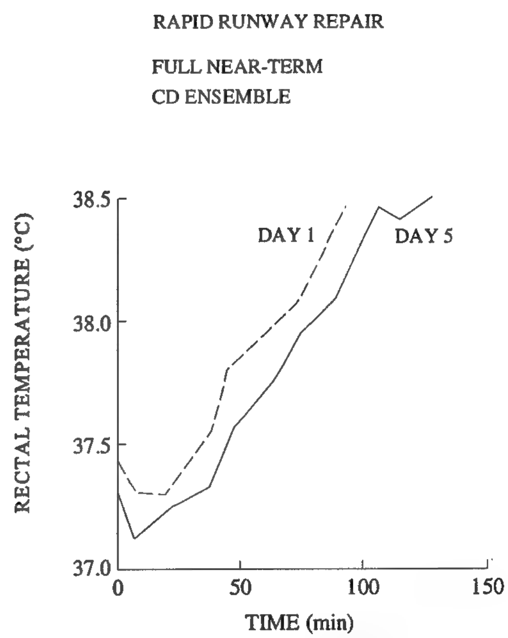

Figure 4a. Effect of training on rectal temperature response during heavy work in the CDE.

Personal observations and interviews of the subjects suggested that mask intolerance, rather than physiological endurance, was the primary factor in limiting military effectiveness in the initial exposure (day 1). The conclusion reached by these

investigators was that none of the casualties incurred on day 1 was due to excessive heat storage. The result of an improvement in performance was attributed to the training. Auxiliary cooling was suggested to further enhance performance by virtue of its ability to eliminate the thermal burden imposed by the CD overgarments. Over the initial 75 min of exposure, T_{re} climbed to a mean value of 38°C, regardless of the experimental condition. Once the mean value for T_{re} reached 38°C in both the Closed w/Cooling and Open conditions, no further body heat storage occurred for more than 2 additional hours (Fig 4c). It was concluded: 1) that the auxiliary cooling provided by the water-cooling system used in this study had eliminated the thermal burden imposed by the CD overgarments and 2) that the data (not reported) for HR and SR tended to support this conclusion. However, no comparisons were made with a true control, i.e., no CDE. These investigators

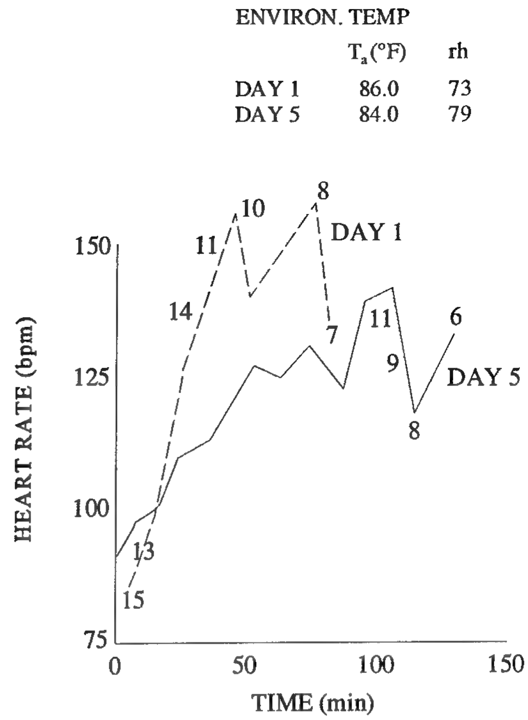

Figure 4b. Effect of training on heart rate response during heavy work in the CDE.

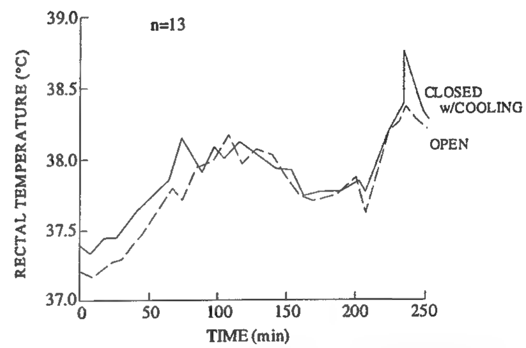

Figure 4c. Rectal temperature response to heavy work while wearing the CDE open and the CDE closed with personal cooling.

concluded that the military effectiveness of a well-trained unit, which must perform strenuous work (RRR exercise) in a full CD posture, can be greatly enhanced by the provision of commercially available portable cooling systems. Unfortunately, the direct effect of "self pacing" on metabolic rate was not quantified here. This omission seriously clouds some of the investigators' conclusions.

Study #5 (Open Loop Freon Cooling Chamber Trials)

Study #5 which was carried out with the collaboration of the U.S. Army (NRDEC, USARIEM, performing labs), evaluated three commercially available, portable microclimate cooling systems. The three selected were: the Model 19 Cool Vest manufactured by ILC Dover, the Cool Head manufactured by Life Support Systems, Inc. (LSSI), and the Thermacor Vest manufactured by Thermacor Technology, Inc. The ILC system was a new configuration; the Thermacor vest represented a new technology. The first two systems relied on melting ice as the sink to remove metabolic heat. The Thermacor system provided cooling by extracting heat from the wearer's body; this heat energy changed the refrigerant (a chlorinated fluorocarbon) from a liquid to a gas.

Five male volunteer soldiers served as test subjects. The environment for each session was maintained at 38°C (100°F) dry bulb temperature and 11.7°C (53°F) dew point (21% relative humidity). The wind speed was 1.13 m/sec (2.5 mph). The test consisted of three 60-minute cycles (50 minutes/10 minutes rest exercise). The subjects walked on a treadmill at 3.0 mph, 0% grade during their 50-minute work

periods. Average measured metabolic rate during the work periods was 440 W. The overall average, including rest, was 384 W. The test subjects wore (in order from the skin outward) a T-shirt, cooling vest, combat vehicle crewman (CVC) fragmentation protective vest, CVC Nomex coveralls, chemical/biological (CB) overgarment (pants and jacket), M-17 gas mask, butyl rubber hood, CB butyl rubber gloves with cotton liners, and CB butyl rubber overboots. The heat absorbed by the Thermacor vest was calculated by weighing the canisters after the test to determine the mass expended. The test was terminated after 180 minutes, when a subject's core temperature reached 39.5°C (103.1°F) or when the heart rate exceeded 180 beats per minute for more than 5 minutes during or immediately following exercise.

The average heat removal rate for each system is shown in Figure 5a. Performance of the ILC and LSSI system were statistically equivalent (244 ± 68 W and 222 ± 29 W, respectively). However, the Thermacor system provided cooling at a significantly lower level ($p < 0.05$) 108 ± 17 W. The average exposure times for each system are shown in Fig. 5b. All values are statistically different from one another ($p < 0.05$). The ILC system allowed for the longest work times. The exposure times differ because some subjects had to be removed from the chambers due to nausea, dizziness, and headaches. The rate at which T_{re} changed differed

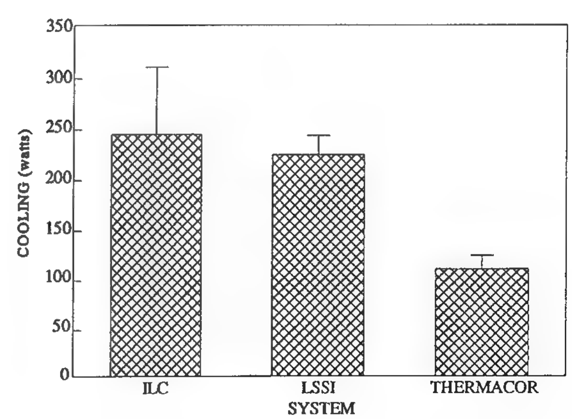

Figure 5a. The calculated cooling values for each system (± S.D.).

significantly between the systems; the Thermacor garment exhibited the most rapid increase in temperature and the ILC system, the slowest (Fig. 5c).

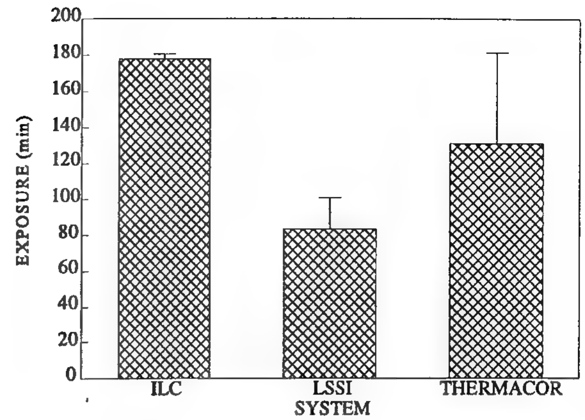

Figure 5b. The observed exposure time in the chamber (± S.D.).

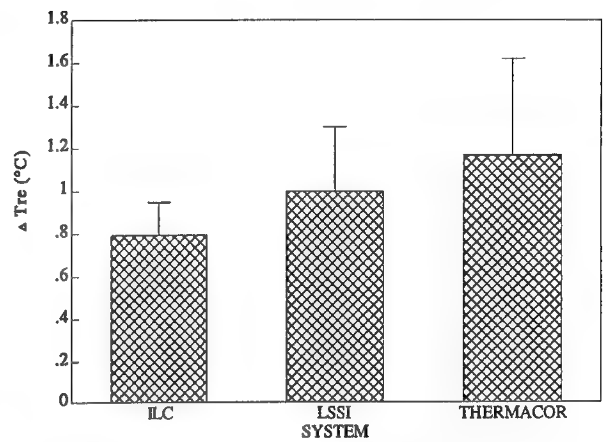

Figure 5c. The observed increase in rectal temperature after 60 min of exposure (± S.D.).

In conclusion, the investigators suggested that all the portable microclimate cooling systems evaluated in this study exhibited features that would make them unsatisfactory for extended field use by the armed forces because of practical and logistical concerns. The LSSI Cool Head allowed for an average exposure time of only 83 minutes despite providing a high rate of cooling. It was suggested that this short cooling period may have been due to the (inefficient) head cooling provided by the system. The Thermacor vest, although providing a greater average stay time for the subjects than the LSSI system, allowed only two of the subjects to continue beyond two hours. The Thermacor system also presented a logistical burden; it is necessary either to purchase, store, and issue canisters of R114 or to develop a closed-loop regeneration system. The Model 19 Cool Vest by ILC permitted the highest stay times in the high temperature environment, but it is actually limited to about two hours because of the

need to leave the contaminated environment and enter a clean environment where the wearer must remove clothing to service the cool vest. Based on the study results, for sorties of short duration (less than two hours), only the ILC system combines an adequate cooling rate with minimal logistical burden. It must be kept in mind, however, that the ILC must be worn inside of the protective garment which make it impractical for widespread field use.

INTERMITTENT COOLING STUDIES

Study #6 (Intermittent Liquid Cooling Chamber Trials)

One approach to enhancing total work capacity is to incorporate carefully scheduled rest cycles into the work task. Realizing the limitations of technology currently available, Study #6 researched the efficacy of employing personal microclimate cooling during the obligatory rest periods via a stationary tether. This approach was expected to greatly accelerate heat removal, while avoiding many of the logistical and ergonomic problems associated with ambulatory, backpack systems.

The eight subjects (five men, three women) who participated in these tests, with the exception of a higher aerobic fitness level, were broadly representative of the United States' general labor population. All observations were performed in an environmental chamber at 38°C T_{db}, 26°C T_{wb}, and 43°C T_{bg} (WBGT = 31°C). The following three clothing conditions were studied in a repeated measures design: (1) control, T-shirt and trousers only (C); (2) chemical protective ensemble (CDE, MOPP IV configuration) without auxiliary cooling (CPE); and (3) CPE plus intermittent liquid

cooling (COOL). The work consisted of inclined treadmill walking with 30 min walking alternated with 30 min of seated rest. The metabolic rate was set at about 40% of VO_{2max} which resulted in a mean work rate of about 475 W gross (400 W, C trial). The "rest" conditions were the same as those for work except no direct source of radiant heat was used to simulate a shaded environment. Walking was stopped if body core temperature reached 39°C or total elapsed time exceeded 240 min. The liquid cooled garment was a snug-fitting, upper torso vest covering approximately 0.5 m^2 of body surface. Chilled liquid was circulated through small-bore Tygon tubing at a rate of approximately 1 L/min, with a fluid inlet temperature of approximately 13°C.

The rectal temperatures at the end of each work and rest cycle across time for each condition are displayed in Figure 6a. Cumulative heat storage was minimized after the first work/rest cycle in the C trial, and after the second work/rest cycle for the COOL trial. For both end work and rest cycles, independently, the responses of core temperature (T_{re}) over time were significantly different ($p < 0.05$) among the three experimental paradigms. Working heart rates were always lower ($p < 0.05$) in the C condition while no significant differences were noted between CPE and COOL condition (Figure 6b). Table 3 shows selected physiological responses after the final

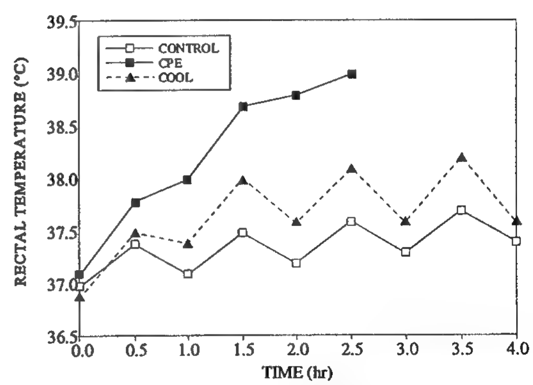

Figure 6a. Mean rectal temperature at the end of each work and rest cycle for three experimental conditions.

work period for each condition. Even more marked differences in body temperature between the COOL and CPE trials can be seen after the final rest period (see Table 4). In general, a review of Table 4 suggests that, when the COOL trial is compared with the CPE trial, the addition of intermittent cooling considerably lowered T_{re} and T_{sk} temperatures relative to the CPE trial.

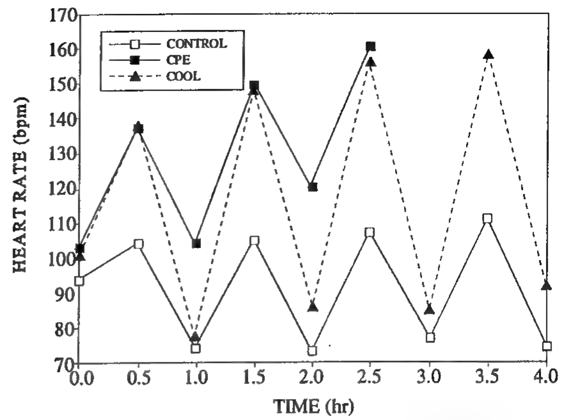

Figure 6b. Mean heart rates at the end of each work and rest cycle for three experimental conditions.

TABLE 3

Physiological Observations at the End of the Final Work Cycle under each Experimental Condition. Mean (± S.E.)

	Condition		
Variable	C	COOL	CPE
Tre °C	37.7 (0.1)	38.2 (0.1)* +	39.0 (0.1)*
Tsk °C (chest)	35.6 (0.1)	37.4 (0.2)* +	38.3 (0.2)*
Tsk °C (thigh)	35.5 (0.2)	37.2 (0.3)* +	37.7 (0.2)*
Heart Rate (bpm)	111 (2.9)	164 (5.8)*	160 (4.2)*

* $p < 0.05$ vs. C
\+ $p < 0.05$ vs. CPE

TABLE 4

Physiological Observations at the End of the Final Rest Cycle under each Experimental Condition. Mean (± S.E.)

	Condition		
Variable	C	COOL	CPE
Tre °C	37.4 (0.1)	37.3 (0.1)* +	38.6 (0.2)*
Tsk °C (chest)	36.6 (0.4)	28.3 (0.9)* +	38.0 (0.1)*
Tsk °C (thigh)	35.5 (0.1)	39.6 (0.3)* +	37.9 (0.3)
Heart Rate (bpm)	74 (2.8)	86 (4.5)* +	114 (5.0)*

* $p< 0.05$ vs. C
+ $p< 0.05$ vs. CPE

Figure 6c indicates a significant increase in sweat production for the CPE condition compared to the other trials. Figure 6d depicts the calculated mean heat removal rates by the cooling vest averaged over all of the 30-min rest periods. Body heat was obviously removed at a much higher rate earlier in the cooling period when skin perfusion and temperature were likely greater.

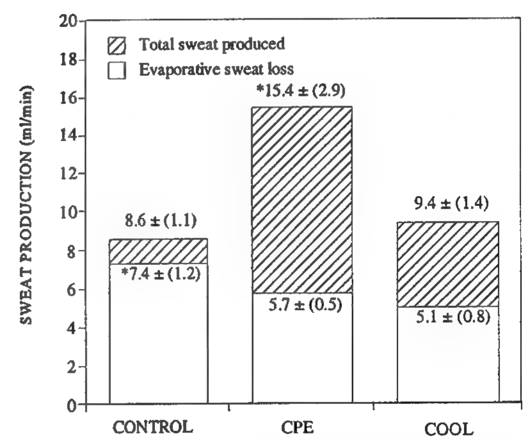

Figure 6c. Cumulative sweat rate and evaporative sweat loss response to intermittent work and rest for three experimental conditions.

The main conclusion from this evaluation of intermittent cooling is that it can significantly improve the body's thermal balance in otherwise physically debilitating environments. Thermal balance is achieved by greatly accelerating the transfer of body heat during the required rest periods.

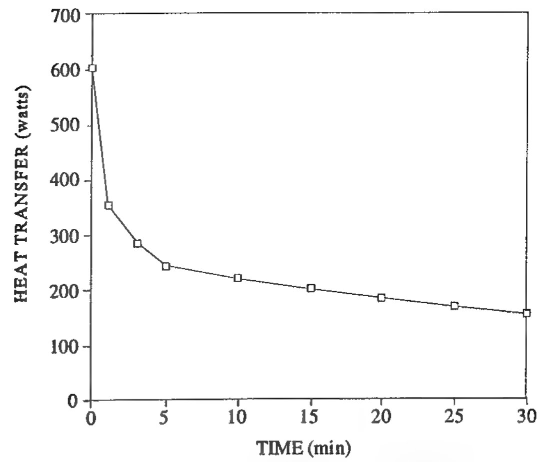

Figure 6d. Mean heat transfer with liquid cooling over time during 30 min of rest across all COOL trials.

Moreover, the required rest time is diminished, thereby significantly improving work productivity. These researchers suggested that shorter, more frequent rest/cool periods may be preferable because both the mean heat storage along with the magnitude of oscillations in T_{re} would diminish over time. The nature of the heat transfer curve also suggests the use of shorter work/rest cycles. Apparently the first few minutes of cooling are by far the most effective; primarily because heat storage, and very likely peripheral blood flow, are both varying in a regressive trend. As the temperature gradient between the skin and the cooling tubes falls, heat transfer declines. Moreover this observation points out the complexity of the biophysical heat removal problem as well as the difficulties in accurately modeling the intermittent cooling situation.

In summary, it was found that intermittent personal cooling during rest breaks was effective in at least doubling treadmill work time. Cost savings could result from incorporating intermittent personal cooling due to the reduced number of personal

cooling systems required, decreased equipment design specifications, and improved work productivity. Therefore, it was concluded that intermittent cooling during rest offered an effective as well as a practical means of reducing heat storage while increasing work capacity, personal comfort, and morale.

Study #7 (Air vs Liquid Intermittent Cooling Chamber Trials)

The purpose of Study #7 was to directly compare the physiological efficacy of intermittent liquid and air microclimate cooling for the reduction of heat stress in subjects performing heavy work under thermally stressful conditions. The subjects for this study consisted of five male and three female volunteers. The work task used for all tests consisted of walking 1.34 m/sec (3 mph) at either a three or a six percent grade. The selected work load elicited approximately 40% of maximal aerobic capacity when the subject was wearing the protective ensemble. Subjects performed the exercise in an environmental chamber where the conditions were 38/24/44°C for T_{db}, T_{wb}, and T_{bg} temperatures, respectively. The work/rest cycles consisted of 30 minutes of walking followed by 30 minutes of sitting. Personal cooling was applied only during the rest periods. The protective clothing worn was the (CDE), worn in MOPP IV configuration. The air cooling vest was that issued to U.S. Army tank crew members. Air was supplied to the vest from a U.S. Army designed cooling unit which produced 15°C air at approximately 500 liters per minute. Outlet air was directed through a flow meter for measurement purposes. The vest received 85% of the air flow with the remainder directed to the face mask. The liquid cooling system consisted of a vest with

48 meters of Tygon tubing in a slip liner covering approximately 0.5 m of body surface area. Water in a mixture with five percent propylene glycol was supplied at a rate of 0.8-1.0 liters per minute to the vest. The coolant inlet temperature ranged from 10°C to 15°C and was delivered by a specially designed cooling system developed by the U.S. Air Force.

The primary focus of this research was to compare two forms of intermittent personal cooling. Data shown in Figures 7a and 7b suggest that in practice both systems performed well, at least under these conditions. In fact, there was a trend for the air cooling to attenuate oscillations in body core temperatures and heart rates slightly more, relative to liquid cooling from cycle to cycle. Work duration was at least doubled, when auxiliary cooling was added. A statistical comparison was made of

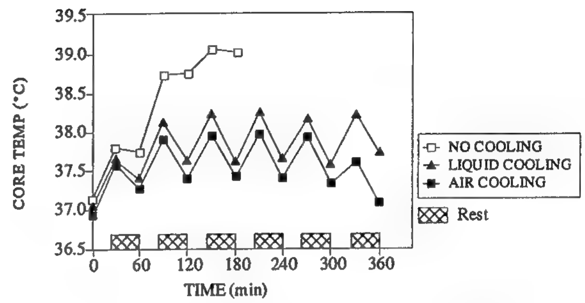

Figure 7a. Mean rectal temperature response to intermittent work under three experimental conditions.

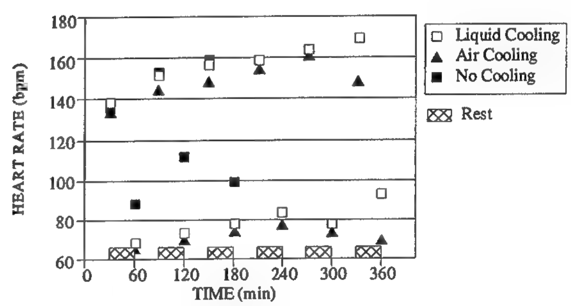

Figure 7b. Mean heart rate responses to intermittent work under three experimental conditions.

certain physiological parameters after the last work and rest cycles (see Table 5). The only significant difference between the cooling perturbations was observed for thigh skin temperature. It would have been expected that the evaporative cooling component

would have been slightly higher with air cooling. Surprisingly, there appeared to be little difference in the effects of the type of cooling on sweat rates or sweat evaporation (see Figure 7c).

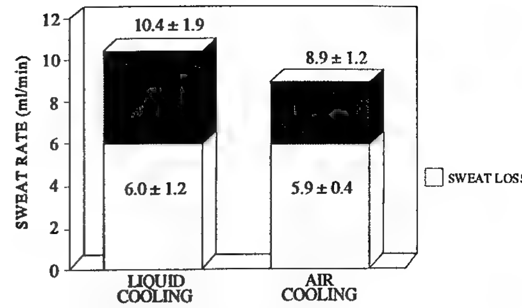

Figure 7c. Sweat production and evaporative loss for liquid and air cooling (±S.E.).

TABLE 5

Final Physiological Parameters and Rating of Perceived Exertion (RPE) Observations. Mean (± S.E.)

	Final "Work"		Final "Resting"	
	Liquid	Air	Liquid	Air
Rectal (T_{re}°C)	38.2 (0.1)	38.0 (0.2)	37.7 (0.1)	37.4 (0.1)
Chest (T_{sk} °C)	37.4 (0.2)	36.9 (0.3)	28.3 (0.9)	29.4 (0.7)
Thigh (T_{sk} °C)	37.2 (0.3)	36.8 (0.2)	36.9 (0.3)*	35.6 (0.3)
Heart Rate (bt/min)	164 (5.8)	156 (7.5)	86 (4.5)	74 (6.7)
RPE Scale (6-20)	13.6 (1.0)	14.9 (0.8)	-	-

* Indicates significant difference between liquid and air cooling, $p < 0.05$.

Under the conditions studied, air and liquid cooling systems were equally effective in reducing body temperatures during intervals of rest. It was noted that air

cooling was preferred by most subjects and appeared to produce drier clothing. The authors concluded that both liquid- and air-cooled systems have good potential for application to problems involving work in hot environments while wearing protective clothing when incorporating the MICS concept.

Study #8 Liquid vs Air Intermittent Cooling Chamber Trials (Warm Temperatures)

In Studies #6 and #7, the U.S. Air Force had examined the use of intermittent microenvironmental cooling during the rest phase of discontinuous work and had also compared liquid and air personal cooling systems for heavy work in hot conditions. The purposes of Study #8 were (1) to examine the efficacy of intermittent personal cooling used during rest periods in subjects engaged in hard work at a WBGT of 26°C and (2) to compare specific liquid and air cooling systems. Subjects for this experiment were 14 volunteers (12 male, 2 female). All testing was conducted in an environmental chamber at a WBGT of 26°C (db, wb, and bg temperatures of 28, 22, and 34°C, respectively). Volunteers walked on an inclined treadmill at 1.34 m/sec with the grade set at a level which elicited a mean energy production rate of 430 W (1.3 L/min), which represented 34% of maximal aerobic capacity. Volunteers walked for 45 min, and then rested for 15 min under the same conditions as the walk, except that they sat away from the direct radiant heat source to simulate shady conditions. This work-rest cycle was then repeated until volitional exhaustion, heart rate (HR) exceeded 180 beats/min, rectal temperatures (T_{re}) reached 39°C, or 4 hr elapsed. Volunteers wore a U.S. military chemical protective ensemble (CPE) for all tests and were tested under three

conditions: NO COOLING, without any supplemental cooling; LIQUID, in which subjects were cooled during rest with a liquid cooling system; and AIR, in which subjects were cooled during rest with an air cooling system. The air and liquid cooling systems were similar to those described in Study #7.

The T_{re} responses across time for the first four cycles are displayed in Figure 8a. The first work and rest cycles for each treatment were very similar. The first work cycles were identical except for the presence of the inactive cooling vests, so no differences were expected. During the second rest, the supplemental cooling began to exert some influence on T_{re}. The HR responses to each successive rest period are displayed in Figure 8b. Cooling during the preceding rest period did not generally influence HR responses at the end of the following work cycle. However, during the rest cycle, HR was significantly reduced for both types of cooling compared to rest without cooling.

Mean walk times and physiological responses at the end of the final work and rest cycles to the three conditions are shown in Tables 6 and 7. Six subjects were able to complete 4 hr of walk/rest under the NO COOLING condition. Two subjects were stopped by investigators because of a T_{re} of

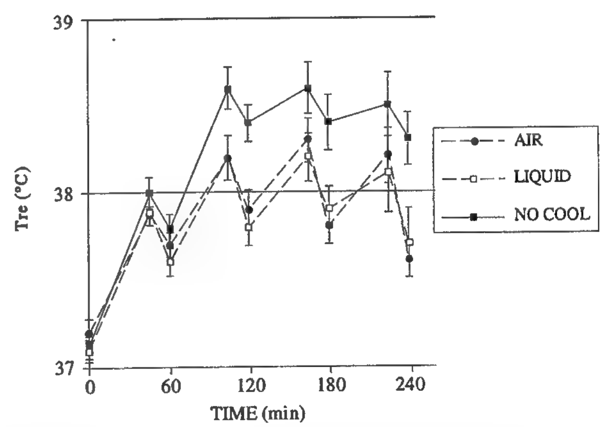

Figure 8a. Mean rectal temperature response to intermittent work under moderate environmental conditions.

39°C. Eight subjects were able to complete 4-hr or more of walk/rest under AIR, and six were able to complete 3-hr or more under LIQUID cooling conditions. No subject reached a T_{re} greater than 38.4°C for either of the cooling trials. The overall sweat production and loss rates are shown in Figure 8c. The total sweat production rate was greater for the NO COOLING trial than for the cooling trials. Absolute sweat loss was not different between trials despite different durations of exposure. Sweat loss as a percentage of sweat production was significantly higher for AIR and NO COOLING.

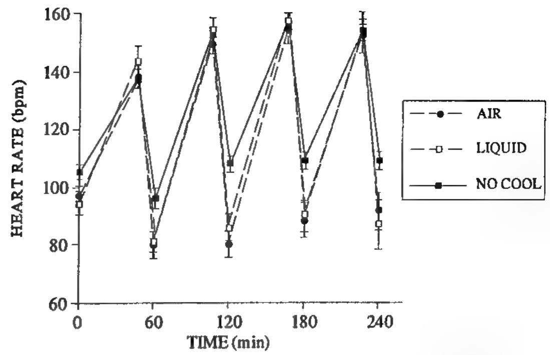

Figure 8b. Mean heart rate responses to intermittent work under moderate environmental conditions.

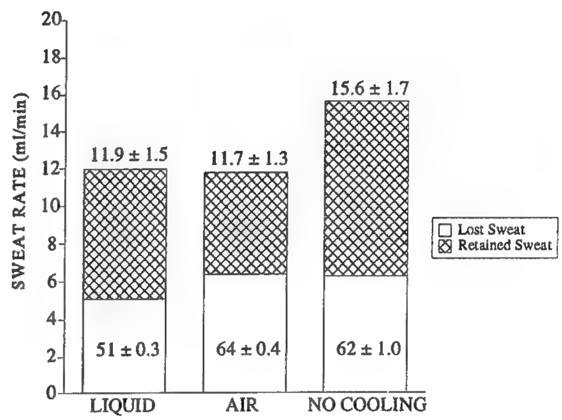

Figure 8c. Mean sweat loss (by evaporation) and sweat retained responses to intermittent work under moderate environmental conditions.

TABLE 6

Physiological Response to No Cooling and Air and Liquid at the End of the Final Work Cycle. (N=14). Mean (±S.E.)

Variable/Condition	NO COOL	AIR COOL	LIQUID COOL
Walk Time (min)	135.0 (11.9)	174.0 (2.5)	156.0 (9.9)
T_{re} (°C)	38.7 (0.1)	38.3 (0.1)[a]	38.4 (0.2)[a]
Chest T_{sk} (°C)	36.9 (0.2)	36.5 (0.2)	36.9 (0.2)
Thigh T_{sk} (°C)	36.6 (0.2)	35.6 (0.2)[ab]	36.2 (0.2)
Mean T_{sk} (°C)	36.5 (0.2)	36.1 (0.3)	36.1 (0.3)
Heart Rate (bt/min)	162.0 (3.4)	157.0 (4.0)	162.0 (3.4)

[a] Shows significant ($p < 0.05$) differences between the AIR or LIQUID and the NO COOL condition.
[ab] Shows significant ($p < 0.05$) differences between the AIR and the LIQUID condition.

TABLE 7

Physiological Response to No Cooling and Air Liquid Cooling at the End of the Final Rest Cycle. Mean (±S.E.)

Variable/Condition	NO COOL	AIR COOL	LIQUID COOL
Rest Time (min)	49.5 (4.1)	58.5 (4.3)	51.1 (3.3)
T_{re} (°C)	38.4 (0.1)	37.8 (0.1)[a]	38.0 (0.1)[a]
Chest T_{sk} (°C)	36.6 (0.2)	29.0 (0.7)[ab]	32.4 (0.4)[a]
Thigh T_{sk} (°C)	36.5 (0.1)	35.1 (0.2)[a]	35.2 (0.4)[a]
Mean T_{sk} (°C)	35.5 (1.0)	31.7 (0.4)[a]	33.7 (0.3)
Heart Rate (bt/min)	112 (2.3)	91.0 (4.9)[a]	96.0 (4.7)[a]

[a] Shows significant ($p < 0.05$) differences between the AIR or LIQUID and the NO COOL condition.
[ab] Shows significant ($p < 0.05$) differences between the AIR and the LIQUID condition.

In general, these researchers found that cooling by either AIR or LIQUID reduced physiological strain compared with NO COOLING under these conditions. After the final rest period, the AIR system appeared to be slightly more effective than the LIQUID in lowering skin temperature. It was noted that perhaps, in longer work durations, this effect might be significant, because there was a trend toward statistically significantly lower T_{re} for AIR compared with LIQUID. Thigh temperatures at the end of work were lower and chest temperatures were not lower in the cooling trials. This finding is somewhat surprising because all cooling was supplied to the upper torso. In Study #6 in which liquid cooling was compared with no cooling, also under hotter conditions (WBGT = 31°C), intermittent liquid cooling effectively doubled work time. Although all experiments in the present study were arbitrarily stopped after 4 hr in the milder environment, AIR cooling increased mean work time by at least 28%, allowing 11 subjects to complete four work cycles, two to complete three cycles, and one to complete one work cycle. LIQUID cooling mean work time increased 16% with six subjects completing four work cycles, seven completing three work cycles, and six completing only two work cycles.

The research team suggested that the smaller increase of work time in the present study may be attributed to the premise that, under (other) hotter conditions, work without supplemental cooling was often limited by high rectal temperatures. At these lower temperatures, fatigue, rather than the T_{re}, seemed to be limiting. The study extended the findings of previous USAF work by showing that the two cooling systems provided similar physiological responses in subjects performing heavy work under

moderate conditions. Consistently, in all of the previous studies, under different combinations of work ratios and environment, air cooling produced a slightly better physiological response than liquid cooling. Based on the results of the present study, the advantages of intermittent personal cooling appear to diminish as ambient temperatures are reduced.

Study #9 (Impermeable Suit Cooling Chamber Trials)

Included in Study #9, two different CWD (groundcrew) "compressed air cooling" suits were evaluated for reduced thermal stress compared to the standard CDE in use. The two ensembles tested were identified by manufacturers, i.e., Bullard and Encon CAC (compressed air cooling) suits. Both garments are completely impermeable (as opposed to the standard CDE) to both liquids and vapors. The Encon CAC suit may be used in two operational modes; either tethered to an air source for (vortex) chilled air delivery, or wearing a backpack blower that delivers ambient air at a rate of 13.4 cfm and weighed 18.4 lbs (36.3 lbs for total system). The assembly incorporated "much heavier material" and incorporated an integral (to the suit) filter blower (2.8 cfm) air distribution system. (total weight of system = 24.2 lbs). Alternatively, it could be connected to a similar air supply employing the integral vortex chiller (tethered mode).

The experimental protocols were initially attempted with six subjects. Protocol I was designed to simulate rapid runway repair (RRR) work loads. The subjects donned each of three CD ensembles on separate occasions: 1) the standard groundcrew CDE (Condition C); 2) the Encon suit (condition E); or 3) the Bullard suit (condition B).

Subjects then walked on a treadmill at 3.3 mph and 5% grade (= 400 kcal/hr) under environmental conditions of 32°C T_{db}, 22°C T_{wb} and 37°C T_{bg}. The wind speed was observed to be quite low. A work rest ratio of approximately 30/26 was incorporated. This protocol apparently equated to three 10 min work bouts interspersed with two 3 min rest periods and followed by a 20 rest period. Under conditions E and B vortex cooled air was supplied to the subject during the 20-min rest period, while the ambient air blowers were functioning during the rest of the time (B+C only). Protocol II differed in several ways. First, six alternating 10 min work/3 min rest periods were used, while after the 6th and 12th work bout, a ten min rest period followed. Only the Bullard suit (condition B) was tested here and vortex cooled air was supplied throughout the entire test. Instead, a second "cooling" trial was accomplished by having the subjects wear a liquid cooling system under the CDE. This was apparently a commercially produced system but was not further described in the original report. Moreover, it was noted that some "supplemental" evaluations were also accomplished using Protocol II whereby "high flow" (HF) vortex cooling was used instead. This HF vortex delivered -10°C air to the wearer at 12 cfm. This was suggested to be an improvement of 2-fold in flow rate along with a decrease of 10°C in inlet temperature over the standard vortex system. However, neither the flow rates or inlet temperatures were stated in the report.

A review of Table 8 demonstrates that neither CAC suit system offers any physiological advantage over the standard CDE tested. Interestingly, the recovery after achieving a T_{re} of 39.0°C is not accelerated by the application of vortex cooling (w/CAC suit) as compared to the CDE trial where the subject recovered in front of an external

fan (Figure 9a). In fact the CAC suits reduced the mean tolerance time by 36%. An additional observation was noted that the subjects experienced "air-hunger" when wearing the suit. The low air flow rate (2.87 cfm) here propagated an increase in [CO_2] within the headpiece to as high as 3.5%. In Protocol II (Table 9), when continuous vortex chilled air cool was applied, there was no improvement over the control trial (condition C). However, there was considerable improvement in hydration levels; sweat rates were reduced approximately 60% with moderate improvement in sweat evaporation efficiency (percentage). Interestingly, these improvements were not as great as those observed with liquid cooling (Table 9). Finally, in the supplemental trials where "high flow" vortex cooling was tried, little physiological advantage was noted (Figure 9b). Work tolerance times here were similar to controls.

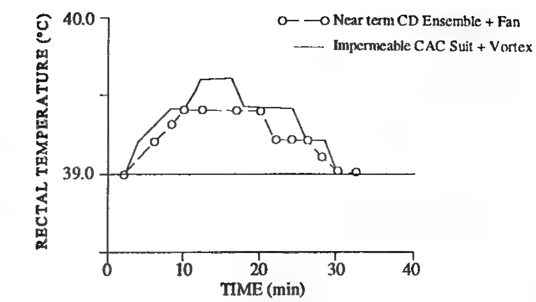

Figure 9a. Duration of rectal temperature overshoot.

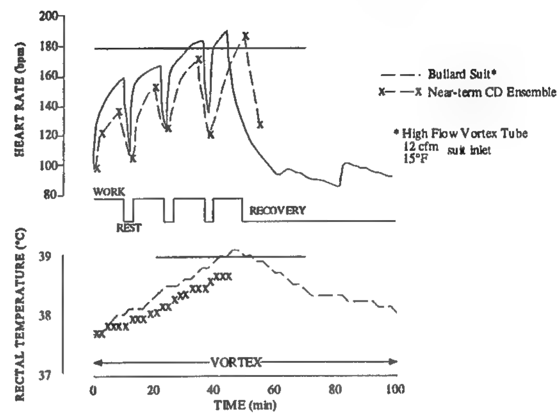

Figure 9b. Physiological responses of one subject to work in the heat.

Overall, the investigators found little if any advantage to the CAC system approach. In fact many physiological and physical concerns were noted about the practical implementation of the CAC concept. It is very important to point out the fact that these suits impose an increased weight (and bulk) on the subject. Accordingly, this

additional burden increases the energy expenditure (and metabolic heat production) required to do the same tasks. Furthermore, the administration of very low temperature air cooling may be somewhat counterproductive by eliciting a peripheral vasoconstriction which would decrease heat flux from the body core.

TABLE 8

Protocol I Test Results.

	Near-Term Ensemble	Encon Suit	Bullard Suit
	N = 5	N = 4	N = 3
Rate of rise in rectal temp. (°C/h)	1.4	1.8	1.6
Rate of rise in mean skin temp (°C/h)	3.8	5.5	6.0
Heart rate at end of work bout:			
#1	128.0	140.0	149.0
#2	144.0	155.0	171.0
#3	158.0	169.0	183.0
Sweat rate(g/h)	660.0	590.0	570.0
%Sweat evaporated	40.0	31.0	48.0
Duration of T_{re} overshoot (min)	30.0	30.0	30.0
Tolerance time (min)	76.0	49.0	48.0

TABLE 9

Protocol II Test Results.

	Near-Term Ensemble	Bullard Suit	Liquid-Cooled
Ensemble weight (kg)	7.0	11.0	13.5
Subjects tested	5.0	5.0	3.0
Rate of rise in rectal temp (°C/h)	1.7	1.5	0.5
Heart rate at end of work bout:			
#1	124.0	143.0	127.0
#2	141.0	157.0	146.0
#3	155.0	168.0	146.0
Sweat rate(g/h)	1400.0	600.0	720.0
%Sweat evaporated	25.0	31.0	42.0
Duration of T_{re} overshoot (min)	No Data	30.0	No Data
Tolerance time (min)	50.0	51.0	>170.0

COMBINED COOLING STUDIES

Study #10 (Continuous Air Cooling, Warm, and Hot Environments)

Study #10 was an attempt to further increase the capacity for heat removal and at the same time decrease cumulative fatigue and discomfort by the use of ambient air cooling during work periods, in addition to the conditioned air cooling during rest periods. The subjects for this series of tests consisted of civilian and military volunteers. The task used for all test batteries described in this paper consisted of walking 1.34 m/sec (3 mph) at either a 3 or a 6% grade with intermittent rest periods. The selected work load elicited approximately 40% of the subject's maximum aerobic capacity. Subjects performed the

intermittent exercise in an environmental chamber where conditions were described in degrees Celsius by measures of dry bulb (T_{db}), wet bulb (T_{wb}), and black globe (T_{bg}) as either warm (n=8) or hot (n=7). These values were as follows: warm conditions = 28,22,34°C; and hot conditions = 38,26,44°C, respectively. The ratio of work to rest was 3:1 for warm conditions and 1:1 for hot conditions. From an absolute time standpoint the work/rest ratio equated to 45:15 min and 30:30 min, respectively. The following three experimental perturbations were employed, subjects served as their own control: 1) no personal cooling during work or rest (no cooling, NC), 2) conditioned air cooling during rest periods only (intermittent cooling, IC) and 3) ambient air cooling during work plus conditioned air cooling during rest (continuous cooling, CC). Criteria for stopping a test were: rectal temperature = 39.0°C, subject's sustaining their individual max heart rate as determined during a VO_{2max} test, volitional fatigue, judgment of the medical monitor, or a total trial time of 240 min. The protective clothing worn was again the military CDE MOPP IV configuration. The air-cooled vest used was developed by the U.S. Army primarily for use with tank personnel and has been cited previously in this report (studies #7 and #8). An open circuit system was used to deliver 18 cubic feet of conditioned air per minute (cfm) at approximately 20°C to subjects during rest periods in the air-cooling trials. Again an accommodation was made to divert 3 cfm away from the vest directly to the face mask. The same system was used to deliver ambient (not conditioned) air during work cycles in the CC trial in addition to the conditioned air during rest periods.

WARM CONDITIONS: In the NC trial total work time was 130 minutes. The addition of intermittent air cooling during rest (IC) significantly increased work time to 159 min while ambient air cooling during work (CC) allowed subjects to work for a mean of 163 min. Mean rectal temperatures (T_{re}) at the end of each work interval for all three cooling conditions are shown in Figure 10a. By work and rest cycle 2, T_{re} during NC was significantly higher than during either CC or IC. Mean heart rates (Table 10) at the end of work cycles did not differ. However, the HR response in the NC condition was significantly higher during rest cycles two, three, and four than when conditioned air cooling was applied (IC, CC). Values for mean skin temperature illustrated in Fig. 10b were significantly lower in the continuous cooling condition than in either NC or IC for work cycles two, three, and four. While during rest intervals mean skin temperatures for the NC condition were also significantly higher.

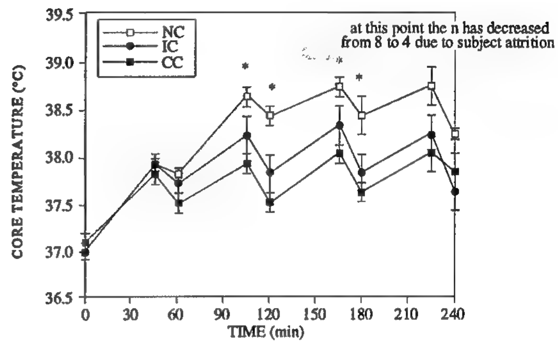

Figure 10a. Mean body core temperature responses to each experimental condition during work and rest in a warm environment.

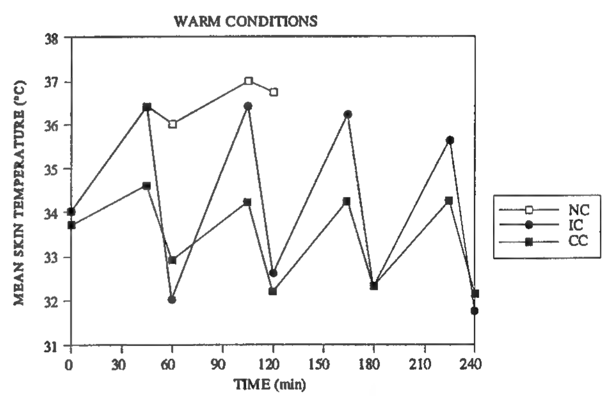

Figure 10b. Mean skin temperature responses to each experimental condition during work and rest in a warm environment.

TABLE 10

Heart Rate at the End of 45-min Work and 15-min Rest Cycles in Warm Conditions. Mean (±S.E.)

	Time (min)								
	0	45	60	105	120	165	180	225	240
NC	102 (2)	144 (5)	93* (4)	154 (6)	109* (4)	161 (5)	110* (2)	161 (5)	108 (6)
IC	99 (5)	144 (5)	79 (4)	154 (5)	79 (5)	160 (6)	92 (8)	160 (6)	109 (7)
CC	98 (6)	136 (6)	78 (5)	139 (7)	84 (6)	140* (8)	81 (8)	140 (8)	85 (9)

* Significantly different ($p < 0.05$) from other two conditions.

Moreover, significant differences in patterns of rectal temperature, heart rate, and mean skin temperature over time during both work and rest cycles were observed due to the greater increases in these variables in the NC scenario. Further, analysis resulted in significant differences between the two cooling conditions for the patterns over time. The implication of these results is that CC was more effective than IC in reducing cumulative heat storage over time. Also, HR values during work and rest cycles were consistently higher in IC than in CC. Mean skin temperatures over time were not different between CC and IC during rest because conditioned air was applied in both cases. Sweat production (SP) rates were significantly lower for the CC condition than for both IC and NC (Fig. 10c). Although sweat evaporation (SE) rates for both cooling methods were similar, the

percentage of sweat produced that was evaporated (SE/SP) was significantly greater for the CC condition than for either of the other two conditions. Subjective ratings for thermal comfort taken during work periods were significantly lower during CC trials than during IC and NC trials for cycles 2 and 3 (Table 11). RPE during the CC trial was also significantly below those taken during the IC trial during the 2nd work cycle and significantly lower than NC ratings during work cycles 2-4.

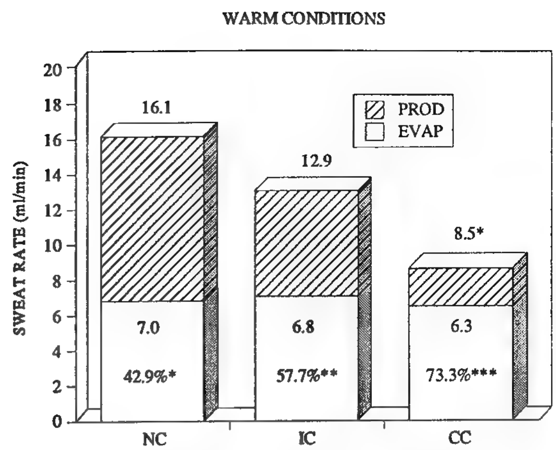

Figure 10c. Sweat production, evaporation, and percentage of sweat produced which evaporated for each experimental trial (Work:Rest = 45:15 min).

TABLE 11

Thermal Comfort (TC) and Ratings of Perceived Exertion (RPE) at the End of 45-min Work Cycles in Warm Conditions. Mean (± S.E.)

Cooling Condition	1		2		3		4	
	TC	RPE	TC	RPE	TC	RPE	TC	RPE
NC	5.25 (.21)	12.9 (1.2)	5.65 (.26)	15.0* (1.5)	5.82 (.35)	15.9* (2.0)	5.23 (.37)	16.5* (1.0)
IC	5.17 (.19)	13.2 (0.7)	5.57 (.18)	14.3* (0.6)	5.75 (.29)	14.8 (0.7)	4.70 (.41)	14.6 (0.8)
CC	4.69 (.21)	12.5 (0.5)	4.87* (.35)	13.3* (0.5)	5.12 (.40)	14.1 (1.0)	5.12 (.49)	14.4 (1.1)

* Significantly different (p< .05) from other two conditions.

HOT CONDITIONS: A mean total work time of 74 minutes in the NC trial was increased significantly to 116 min during the intermittent cooling and continuous cooling trials. As is illustrated in Figure 10d, rectal temperature in the NC trial was significantly higher than IC or CC by the first rest cycle, and remained so during both work and rest until the termination criterion was reached. Heart rate responses during work cycles appeared to differ less between the experimental perturbations. Unfortunately, during this trial, forearm and calf temperatures were not recorded for all subjects.

However, comparisons of thigh and chest skin temperature for each condition are illustrated in Figure 10e. During work cycles the NC chest temperature is not different from the intermittent cooling condition. Both of these levels are higher than the CC condition rest cycles; NC chest temperature is significantly higher than either CC or IC due to the application of conditioned air. Additionally, CC chest temperature is also higher than the IC

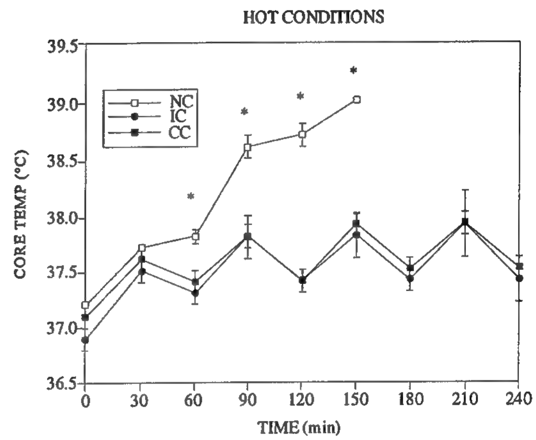

Figure 10d. Mean body core temperature responses to each experimental condition during work and rest in a hot environment.

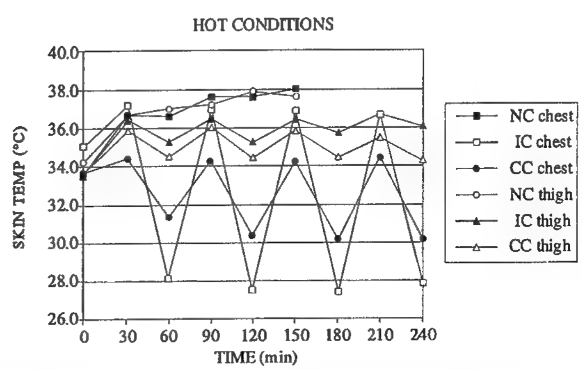

Figure 10e. Mean chest and thigh temperature responses to each experimental condition during work and rest in a hot environment.

chest temperature. The difference in thigh temperature among the three conditions was not as extreme since the air from the cooling vest is not blowing directly on this area of the body. Using a three-way ANOVA, these researchers found significant differences in patterns of rectal temperature, and skin temperature over time during both work and rest cycles. The response for heart rate over time showed similar characteristics with no significant differences between the values for CC and IC (Table 12). Thermal comfort (TC) ratings (Table 13) were significantly lower for CC than for IC during each work cycle. RPE values tended to be lower in the CC condition, although this difference was not always significant. Analysis of sweat rates showed that SP for the CC condition was significantly lower than for NC, and was lower, but not significantly, than IC values. SE rates were similar for all three cooling methods, however, percent evaporation was again significantly greater for CC than IC and NC (Fig. 10f).

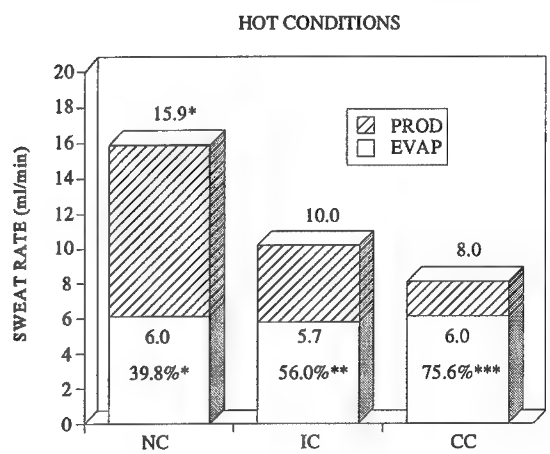

Figure 10f. Sweat production, evaporation, and percentage of sweat produced which evaporated for each experimental trial (work:rest = 30:30 min).

Table 12

Heart Rate at the End of 30-min Work and 30-min Rest Cycles in Hot Conditions. Mean (±S.E.)

	Time (min)								
	0	30	60	90	120	150	180	210	240
NC	102 (3)	135 (5)	93* (5)	152* (5)	113* (8)	160 (14)			
IC	93 (3)	126 (6)	66 (5)	140 (7)	65 (3)	142 (9)	69 (5)	143 (11)	75 (9)
CC	92 (6)	123 (2)	70 (6)	131 (3)	74 (9)	135 (4)	72 (6)	138 (6)	79 (7)

* Significantly different ($p < .05$) from other two conditions.

TABLE 13

Thermal Comfort (TC) and Ratings of Percieved Exertion (RPE) at the End of 30-min Work Cycles in Hot Conditions. Mean (± S.E.)

	1		2		3		4	
	TC	RPE	TC	RPE	TC	RPE	TC	RPE
NC	--	12.0 (0.4)	--	13.6 (0.7)	--	15.5 (1.7)	--	--
IC	5.6 (0.2)	12.4 (0.8)	5.8 (0.2)	13.4 (0.5)	5.8 (0.1)	14.0 (0.5)	5.8 (1.9)	14.1 (0.9)
CC	4.8* (0.2)	11.6 (0.6)	5.0* (0.2)	12.2* (0.7)	5.1*(0.2)	12.9* (0.9)	4.8* (0.3)	12.5 (1.1)

* Significantly different ($p < .05$) from other condition(s).

Overall, in both environmental settings, IC and CC significantly increased work times and appeared to decrease thermal strain, as is demonstrated by lower T_{re} and HR during work and rest, compared with NC responses. Additionally, in the warm

environment there was a significant trend for subjects to better maintain "thermal equilibrium" over time during CC than in IC: that is, to minimize cumulative heat gain across the trial. CC also appeared to allow a more complete physiological recovery during rest than did IC, even though identical conditioned air was supplied during rest in both cases. It was suggested that this inconsistency is probably due to the fact that lower T_{re} and HR values were observed prior to starting each rest cycle in the CC trial. The hotter (38°C) ambient air delivered during work did not appear to give as much physiological relief as the warm (28°C) air. However, the subjective, or psychological, relief was still evident here as is indicated by improved TC and RPE ratings. Furthermore, in calculating the sweat evaporation to production ratio (E/P), the E/P ratios seen in this study (averaged for both temperatures) were 74% for CC, 57% for IC and 41% for NC, and would appear to correspond well to the subjective ratings assigned under each condition.

These results imply a greater degree of overall comfort for the subjects when ambient air cooling was also applied. The researchers noted that subjects generally commented that they were "more comfortable", and "not working as hard" when they received ambient air during work in addition to conditioned air during rest (CC), in both warm and hot environments. It was suggested that the psychological advantage may be as great as the physiological benefit of CC especially under hot conditions. Moreover, ambient air cooling during work provides additional toxic agent protection by producing a modest overpressure within the CD ensemble.

Study #11 (Continuous Air Cooling Hippack Chamber Trials)

Study #11 describes the system and physiological testing of a very lightweight, human-mounted air cooling approach. An ambient air cooling unit which can provide adequate clean air was developed and tested in a controlled thermal chamber. Study #9 (this report) first evaluated this concept of "continuous cooling" by simulating the ambient air flow and not wearing an actual cooling unit. The cooling unit is composed of a battery-powered vacuum blower, battery set, air plenum, control panel, 3 Army C-2 filters, and support frame. This compact "belt pack" unit weighs approximately 8.5 pounds with battery and provides 12 cubic feet per minute (cfm) filtered ambient air through a U.S. Army developed air vest (10 cfm to the body and 2 cfm to the face). The unit is energized by a 24 Volt 2.2-ampere battery activating a one-stage blower which draws ambient air through three canister filters for up to three hours of continuous operation. This system is ergonomically balanced on the individual's hips with shoulder supports and does not appear to interfere with normal job performance. The unit may be used independently or in conjunction with the multiman intermittent cooling system (MICS) approach. The seven subjects used for the series of tests were military volunteers. Subjects wore the Army air vest over a cotton T-shirt and under the battle dress uniform and the military chemical defense ensemble (MOPP IV configuration). The physical work consisted of walking at 3 miles per hour (4.8 kilometers per hour) and 3-6% grade of the treadmill, which elicited approximately 40% of subjects' VO_{2max}. Subjects performed either intermittent or continuous exercise in a thermally controlled chamber under warm conditions (32°C, 40% RH) until reaching limits of rectal temperature (T_{re}) 39.0°C, heart rate (HR) 180 bpm, or

volitional fatigue.

For intermittent work, three experimental conditions were employed: 1) No Cooling (NC): Subjects completed the intermittent exercise periods without any personal cooling during work or rest cycles, 2) Intermittent Cooling (IC): Subjects received conditioned air cooling during rest periods, but walked on the treadmill without ambient air cooling, and 3) Continuous Cooling (CC): Subjects wore the operational ambient air cooling unit during work periods and also received conditioned air cooling during rest periods. In this intermittent work scenario, four cycles of 40 minutes work (450 Watts) and 20 minutes rest were attempted at each condition. Subjects received 18 cfm of conditioned air (15.5°C-18.3°C) during 20 minutes of rest for the IC and CC conditions. In a second set of experiments during continuous work, subjects walked on the treadmill continuously until reaching one of the termination criteria specified previously. Two experimental conditions were observed, 1) no personal cooling (NC): ambient air cooling unit not employed, 2) ambient air cooling (AC): again subjects carried a functioning ambient air unit.

During the intermittent work scenario where subjects attempted four hours of work/rest cycles, all seven subjects completed at least 80 minutes in the NC trial. Analysis of these data indicated that individuals who received cooling in the IC and CC trials performed better than in the NC condition relative to the physiological measures of heart rate, skin temperature, core temperature, and heat storage. Increases in rectal temperature and mean skin temperature observed over the first three work periods tended to be greater during IC than CC (See Figs. 11a and 11b). Although there were no

differences in heart rate during the work cycles, the average heart rate during rest cycles with CC was lower than for IC (See Fig. 11c). Heat storage values were not statistically different between CC and IC during 140 minutes of intermittent work; however, the data suggest that physiological differences may exist since CC values tended to be consistently lower than IC measurements (See Fig. 11d). Using ambient air during work cycles helped to keep skin temperature lower than under the IC and NC conditions. As indicated in Figure 11e, sweat production rates (SP) were significantly lower for CC and IC than for NC; the rate for CC was lower than for IC. Additionally, the sweat evaporation rate for CC was higher than for IC and NC.

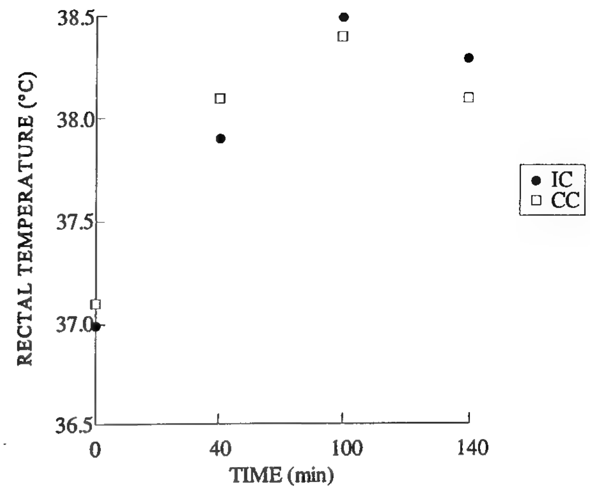

Figure 11a. Rectal temperature responses at the end of each work cycle with intermittent cooling (IC) or continuous cooling (CC).

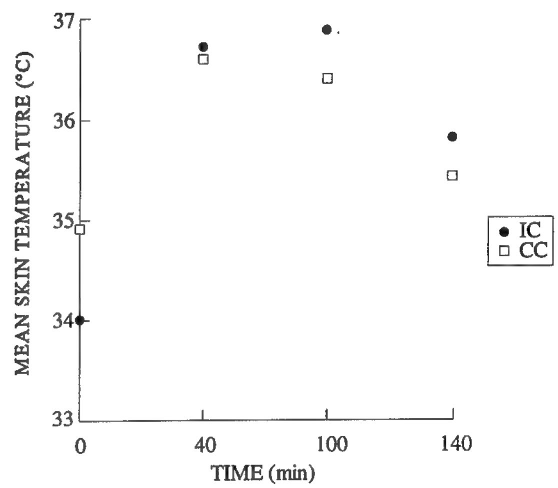

Figure 11b. Mean skin temperature responses at the end of each work cycle with intermittent cooling (IC) or continuous cooling (CC).

During 50 minutes of <u>continuous</u> work, use of ambient air cooling (AC) resulted in a significantly lower increase in heat storage (Fig. 11f). Mean skin temperature (Fig. 11g) was also significantly higher in the no cooling (NC) trial. AC had a significant effect on

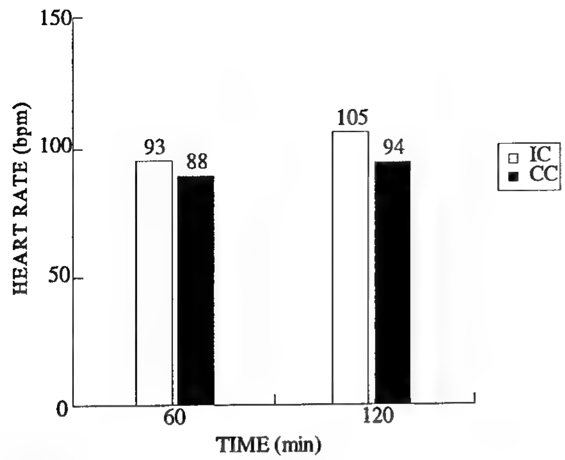

Figure 11c. Heart rate responses at the end of the first two rest cycles with intermittent cooling (IC) or continuous cooling (CC).

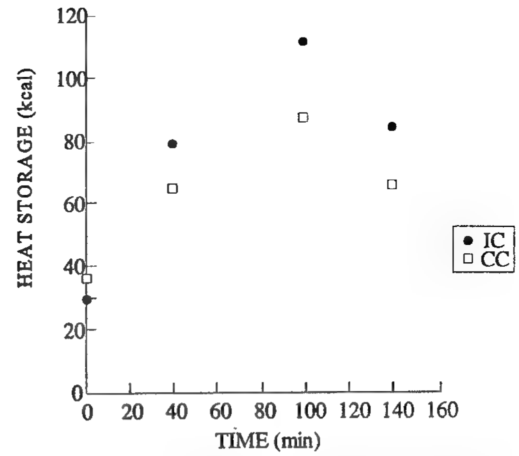

Figure 11d. Calculated heat storage values at the end of work cycle for intermittent cooling (IC) or continuous cooling (CC).

lowering thermal comfort ratings (TC), which was evident even at the 10-minute point (See Fig. 11h). Sweat production rates (SP) were not different for AC and NC. However, there was a significant difference in sweat evaporation (SE) and percent of sweat evaporation (Fig. 11i).

In summary, all cooling scenarios (AC, IC, CC) decreased thermal strain compared to no cooling trials. Significant differences between continuous cooling and intermittent cooling were observed in the following measures: skin temperature, heat storage, and sweat evaporation

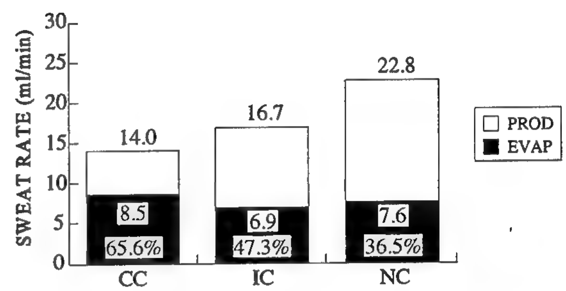

Figure 11e. Sweat production, evaporation, and percentage of sweat produced which evaporated for each experimental trial.

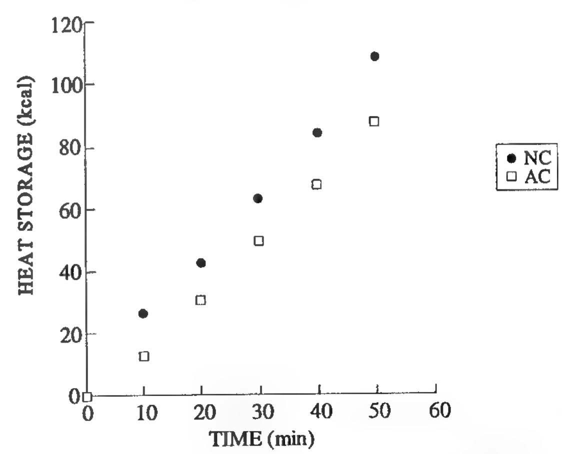

Figure 11f. Calculated heat storage values during continuous work. AC = Ambient air cooling; NC = No cooling.

efficiency. These investigators suggested that the 8.5-pound load experienced by subjects carrying the ambient air cooling unit during work periods might have counteracted some of the expected physiological and psychological benefits from ambient air cooling. Moreover, the filtered ambient air gained heat from the motor and control panel which increased inlet air temperature approximately 2-3°C. Therefore, it was suggested that skin temperature and the resulting thermal perception may also have been somewhat compromised. Interestingly, most subjects commented that air flow to the face was inadequate during work.

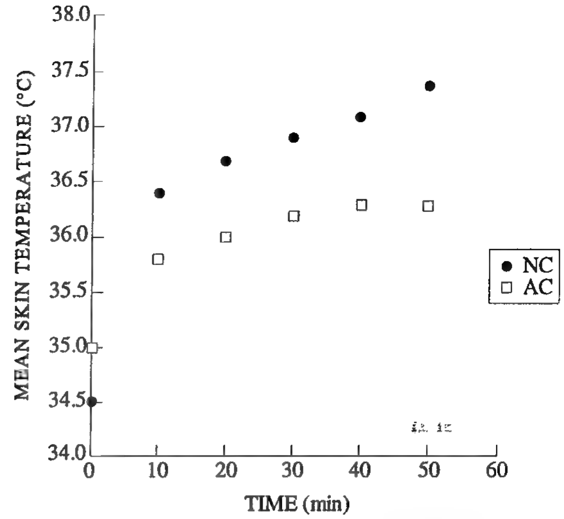

Fig 11g. Mean skin temperature responses during continuous work. AC = Ambient air cooling; NC = No cooling.

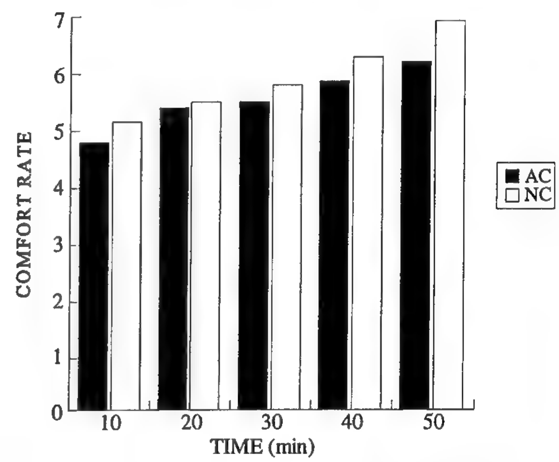

Figure 11h. Thermal comfort ratings during continuous work. AC = Ambient air cooling; NC = No cooling.

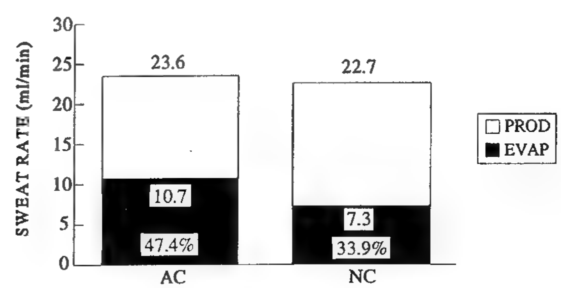

Figure 11i. Sweat production and evaporation rates during continuous work. AC = Ambient air cooling; NC = No cooling.

CONCLUSIONS

It has been the general scientific consensus to date that the concept of personal cooling systems show some promise with regard to the problem of heat stress while wearing the CDE. However, most researchers agree that the ideal system has yet to be developed. Commercially available systems have been earlier shown to be not operationally suitable for the USAF. The cooling systems developed by the USAF have been an improvement over previous apparatus tested, but are still less than ideal. Several distinct shortcomings still exist with the systems described in this report. For example, all of the self-contained systems would have limited cooling power which should prove insufficient under highly stressful conditions. The rationale for this projection is that the number of metabolic calories of heat that would be generated during heavy work may be as much as double the estimated maximum removal rate of the back-pack systems. Other sources of heat removal, i.e., evaporation, may not be able to make up this difference and might contribute very little when the environmental conditions are harsh (i.e., very high humidity). This also assumes a 100% efficiency of the systems. Furthermore, the maximal sustained capability of the cooling garment (vest) has not yet been fully determined; this may be a highly limiting factor in and of itself, regardless of the cooling power of the chiller unit. Most likely a vest-size garment will be able to remove only a percentage of the metabolic heat load. On the other hand, it is important to remember that a significant amount of cooling appears to be within the present technologic capabilities, which could be of some help for selected operational scenarios.

Complicating this personal cooling problem is the issue of the logistical support involved with the deployment of any system. This latter concern stems from the frustration experienced during testing by both the development personnel and the using commands. This is not a simple problem. Overall, the reliability of any of these systems is unproven; however, some of the components employed have already been used commercially. The ice pack is obviously the least complex, but the feasibility of continuously refreezing these units in the field has been questioned. This latter consideration seriously complicates utilitarian aspects of an ice sink. Therefore, supporting any of these backpack systems in the field may prove to be a logistical nightmare. Obviously it is important not to develop a system that may work in a laboratory environment but could not be supported in the field.

In conclusion, the USAF approaches to the thermal stress problem due to the CDE wear have been presented. This is a truly difficult problem and no ideal system has been identified. Nevertheless some significant amounts of externally supplied cooling are probably within prototype capability with the current technology. Limited deployment of certain systems might be the most attractive option for the near future. Thus far, the intermittent cooling approach along with ambient air chillers have shown the greatest promise in the near-term for many USAF applications.

ADDENDUM

It should be noted that evidence was located concerning two other Air Force research efforts in this area. However, because of a lack of information regarding this work, they have not been formally included in this report. They are listed below.

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